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Architectural Design of Building Components for Earthquakes

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- The Dynamic Environment, which describes the nature of the seismic motions that a component will be subjected to in a particular location of a building. Any given component will have its own particular Dynamic Environment.

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- In a case study of an enclosure wall system, design objectives are defined, alternative design concepts studied, and the wall designed to meet the given seismic design criteria,
- A study of selected ceiling and partition systems defines generic ceiling systems and partitions, discusses their possible responses to input motions, identifies potentially damaging responses, and suggests means of achieving compatibility between systems.

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Abstract

Review of the dynamic principles governing site and building response provides the basis for a conceptual model of building and component interaction during earthquakes. This conceptual model consists of:

- A four-part Dynamic Model, which describes the various elements of a building, their interactive relationships during earthquakes, and the effect of their interaction on overall building response.
- The Dynamic Environment, which describes the nature of the seismic motions that a component will be subjected to in a particular location of a building. Any given component will have its own particular Dynamic Environment.

The conceptual model is then applied to architectural design procedures; two studies illustrate the design of building components according to the principles of the model:

- In a case study of an enclosure wall system, design objectives are defined, alternative design concepts studied, and the wall designed to meet the given seismic design criteria.
- A study of selected ceiling and partition systems defines generic ceiling systems and partitions, discusses their possible responses to input motions, identifies potentially damaging responses, and suggests means of achieving compatibility between interacting systems.

Summary of the Report

Introduction and Conclusions. These sections introduce the reader to the range of topics covered in the report and point out the major conclusions reached by the authors that should be kept in mind while reading the various studies.

Chapter One - Earthquakes and Building Response. This chapter presents an overview of the earthquake phenomenon and site and building response. The nature of ground shaking and building response is presented in a qualitative manner, and the principles and terms used to describe those phenomena are introduced. The principles discussed in this chapter are the basis for the conceptual model of building component interaction introduced in Chapter Two. This chapter is intended to provide a minimum conceptual understanding of dynamic interaction to architects and others who have limited knowledge of structural dynamics.

Chapter Two - The Dynamic Model of Building Component Interaction and the Design Process. A Dynamic Model is introduced that utilizes dynamic principles to describe various interactive roles between building components. Every component in a building will have an interactive role described by the Dynamic Model, and must be designed for its Dynamic Environment, the motions to which it may be subjected during an earthquake. The effect of the Dynamic Model on the design process is then explained in terms of overall building design, and the Dynamic Environment further described as it affects the detailed design of individual components.

Chapter Three - Building Response and Component Design: An Enclosure Wall Case Study. This chapter illustrates use of the Dynamic Model when it was in its preliminary stages of development. The Model was used as an aid in the design of an enclosure wall for an actual building

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being designed concurrently with research done under the study team's first NSF grant. Included in the case study are descriptions of the seismic conditions imposed by the site, design of the basic structural system, detailed component design, mock-up testing, and fabrication and construction of the enclosure wall at the actual site. All of these activities are described in terms of the effect of the Dynamic Model on the design process.

Chapter Four - Design of Ceiling Systems and Partitions for Their Dynamic Environments. Utilizing the concepts and procedures developed in Chapters One and Two, an analysis is made of typical commercial/institutional ceiling systems and partitions. Ceiling systems and partitions are examined for their physical properties that will determine their dynamic characteristics; next, their probable response to input motions is studied. Finally the systems are analyzed in their various combinations to determine what interface conditions are necessary for the systems to interact during earthquakes without significant damage.

Appendices. Appendix A is a more detailed presentation of some important aspects of site, building, and floor response phenomena. The information is semi-technical and intended for readers familiar with the concepts presented in Chapter One. Example No. 1 is a study of the possible effects of site conditions on building response; Example No. 2 discusses the effects of a building's stiffness on its response to input ground motions; Example No. 3 compares actual records with analytical studies of building response; and Example No. 4 presents the potential effects of floor response on component response. Appendix B summarizes the two major methods used by engineers to calculate the response of multi-degree-of-freedom building structures.

Preface

This report is intended for architects and those in related disciplines whose professional responsibilities require them to understand the nature of earthquakes and their effects on building design and performance. Selected topics are presented that discuss the effect of dynamic principles on the architectural design process, and that set a precedent for improving design and detailing of architectural components for seismic motions. The information presented does not comprise a textbook because only some of the topics with which architects may be concerned when they design buildings for earthquakes are presented in depth. Neither is this study a design manual: much of the research presented is conceptual and must be empirically tested before new guidelines for architectural design can be recommended with a desirable level of confidence. The authors hope that this study will help architects to become more aware of dynamic principles and their effects on the building design process and that, as a result, architects will be encouraged to seek new design solutions that are not only economically, aesthetically, and functionally feasible, but also yield better building response to earthquakes, and hence result in increased life-safety for occupants and reduced costs of repair and replacement in buildings.

In 1975, McCue Boone Tomsick (now MBT Associates), architects and planners, of San Francisco, and Engineering Decision Analysis Company (EDAC) of Palo Alto, undertook a collaborative investigation of the interaction of building components, sponsored by the National Science Foundation (NSF), Research Applied to National Needs (RANN). The work done under this grant developed a conceptual model of building component interaction, which was presented in a final report, The Interaction of Building Components During Earthquakes, January 1976. Beginning in 1976, MBT Associates undertook further investigations under a second grant from NSF RANN. Gerald M. McCue served as principal investigator, Ann Skaff as research associate and project coordinator, and John W. Boyce as research associate. Engineering Decision Analysis Company was the technical consultant to the MBT team. This report on the second grant, then, builds upon the work of the first grant, and its first objective is to present the basis for the conceptual model developed in the first study, and then to incorporate that model into the design process. The second objective of this study is to apply the conceptual model to the design and analysis of architectural building components in order to test the model's accuracy and efficacy.

The main body of this report is divided into four chapters: the first is a basic theoretical background of dynamic principles; the second, a presentation of the conceptual model and its place in the design process; third, a case study utilizing the conceptual model in the design of an actual building component; and fourth, a case study utilizing the model to study the interactive nature of ceiling systems and partitions. Although the chapters are arranged in a logical order based upon theory and application, each chapter is essentially complete within itself and may be read as an individual study. The studies are presented in a manner that is sufficiently technical to be reasonably precise, and yet qualitative enough so that architects may readily understand the material presented with relatively little knowledge of dynamics or earthquake engineering and design. In some cases qualitative discussions are used because they best communicate the material in a format useful to architects; in other instances, specific technical terms and formulas provide the shortest, clearest, and most accurate information on a given topic. New terminology has been kept to a minimum: most terms that are introduced are closely related to engineering and/or architectural terms already in use for the given topic. The major source of new terms is the conceptual model, which required new terms because architectural design for building components in a dynamic context is a relatively new topic with little theory or terminology of its own. The study team's use of the conceptual model during the course of this study suggested some changes in the model's terminology from the first report in order to describe more accurately the dynamic behavior of building components; these changes have been adopted in this report.

We would like to acknowledge and thank the many people who have assisted us in various ways. Charles C. Thiel, Jr., John B. Scalzi, S.C. Liu, and Henry J. Lagorio of NSF RANN provided helpful advice and support. EDAC engineers Garrison Kost and John W. Reed provided working papers and background studies as well as important criticism of the report drafts; they have made a conscientious effort to advise the architectural team, but they should not be held responsible for any errors that may still remain. Anne Vernez-Moudon, who was project manager of the earlier study, and Alan R. Williams and other members of the MBT staff reviewed early working papers and drafts. James Theimer rendered the illustrations, Martin Gicklhorn supervised layout and paste-up of the final copy, and William Skaff provided editorial assistance. We especially thank Nicholas F. Forell of Forell/Elsesser structural engineers, Eugene O. Tofflemire, and David C. Boone for their assistance

in the preparation of the enclosure wall case study. And finally, George P. Simonds, Karl V. Steinbrugge, and John A. Blume are remembered as the colleagues who first started the principal investigator on this quest.

G.M.M.
A.S.
J.W.B.

Table of Contents

Chapter One Earthquakes and Building Response 9

Chapter Two The Dynamic Model of Building Component Interaction and the Design Process 45

Introduction and Conclusions

Introduction

In the years following the 1971 San Fernando earthquake, studies indicated that the interaction of "structural" and "nonstructural" building components was a significant cause of damage and one little examined by research efforts. Damage occurred to buildings designed according to code and conventional good practice because of unanticipated interaction between building components. In some instances structural systems withstood earthquakes without serious damage, but their motions caused damage to other building components; in other cases structural systems were damaged by interaction with what had been considered to be nonstructural components.

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Most design procedures and building codes do not provide architects with adequate guidance for designing for the interaction of building components. Buildings are often designed as if they were an assembly of separate functional components that meet criteria for static conditions; dynamic conditions are approximated by the addition of horizontal static loads. The result of this procedure is that primary aspects of dynamic interaction are not adequately considered in the design of buildings and their components.

Because buildings are so complex, anticipating the response of all of their components to earthquake input motions is difficult, thus complicating their design for such motions. However, despite the complexity of structural dynamics as a science, and the number of variables in the design of most buildings, some general dynamic principles may be applied to the design process to improve it significantly when compared to traditional static design procedures.

Consideration of dynamic principles in building design requires the designer to realize that the building site, the building, and all of the building's components may experience violent vibratory motions during an earthquake. All parts of a building interact with other parts and, regardless of their intended use, affect the building's overall response to input motions. Based upon these assumptions, the design process then becomes one of analyzing the potential of various components for interaction, and, with the aid of the structural engineer, estimating their potential deflections, displacements, and accelerations. Knowing this information, one may determine, with the aid of the Dynamic Model presented in Chapter Two, the appropriate role of various building components during seismic conditions, and then design the components accordingly.

In this study, specific examples of both design and analysis follow Chapter One, "Earthquakes and Building Response," and Chapter Two, "The Dynamic Model of Building Component Interaction and the Design Process." Chapter Three, "Building Response and Component Design: An Enclosure Wall Case Study," describes an early application of the concepts of the Dynamic Model to building design. Because of programmatic requirements, the case study does not show the range of design alternatives for the enclosure wall for dynamic conditions; however, it does illustrate the need for architects to define more carefully the displacements, deflections, and accelerations to which individual building components will be subjected.

The analyses of ceiling systems and partitions located in relatively "flexible" buildings in Chapter Four, "Design of Ceiling Systems and Partitions for Their Dynamic Environments," are based upon the principles of interaction discussed in Chapters One and Two. The analyses illustrate methods of studying the interaction of building components according to dynamic principles; the analyses are qualitative and such interaction should also be studied empirically. Chapter Four discusses the interaction of ceiling systems and partitions with each other and the structural system of the building; many other building components may interact with these systems and should be included in analysis and design. The dynamic principles and design procedures for these other systems will be similar to those presented for ceilings and partitions.

Conclusions

As a result of the studies in Chapters One through Four, the authors reached some general conclusions that should be kept in mind while reading the various studies:

- A rational design process based upon dynamic rather than static principles, as represented by the Dynamic Model, gives guidance to designers that is not provided by current design methods or codes.
- Codes and design methods should devote more attention to possible amplifications of component response. Although amplifications are considered in the interaction between the ground and a building, such effects also occur between the various components of a building.
- Every building component has its own stiffness that will determine the amount that it will deflect or displace

relative to other components. Because current codes provide only for deflection due to a constant lateral load, damage is likely to occur during seismic interaction at the interface between two components. This problem is further complicated by some recent local code provisions that require bracing of ceiling or mechanical equipment systems for stability. When such braced systems are, in turn, rigidly connected to partition systems located in a flexible building, relative displacements between floors cannot be accommodated, and damage results.

- Based upon the investigations of Chapter Four, the design and detailing of building components to endure, with little or no damage, input motions due to moderate earthquakes promises to be feasible both technically and economically.

Chapter One

Earthquakes and Building Response

Earthquakes cause rapid, intense vibratory motions in the ground and in buildings. Because most people have never experienced a severe earthquake, they have difficulty imagining the violent motions that a building may exhibit. Normally building environments are experienced in a static state, and therefore one's intuitive sense of how buildings should be constructed may not be adequate for earthquake conditions. Persons who design, build, or make decisions about the use or maintenance of buildings must have an understanding of the practical and theoretical principles that govern building motions during earthquakes.

Understanding the principles that govern building dynamic response is important for those who design, build, or make decisions about the use or maintenance of buildings.

The motions that occur in a building during an earthquake

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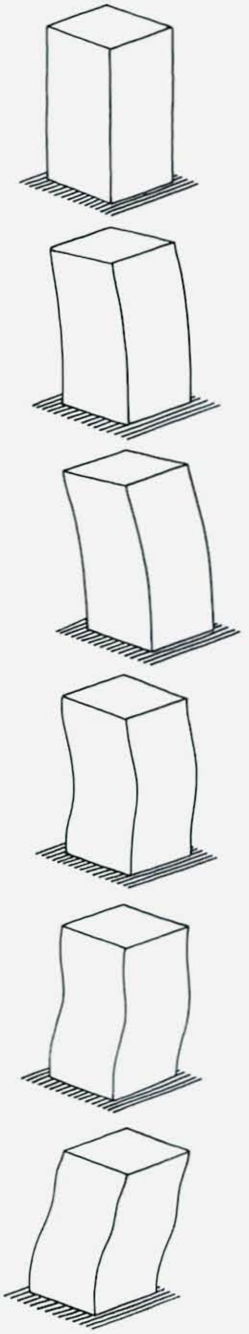
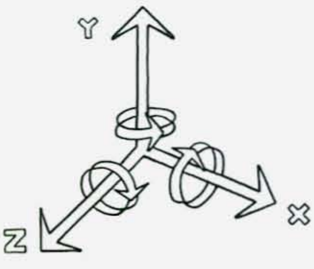


are the result of dynamic interaction between the ground and the building's components. Stress waves emanating from movement along an earthquake fault cause ground shaking, which for a particular geographic location is called the characteristic site response. Ground shaking forces buildings to vibrate and the resultant motions and deformations are called building response. The response is not uniform throughout the building: each portion of the building will have its own characteristics of response, for which that portion's components must be designed.

The interaction between the ground, the building as a whole, and individual building components is described in this chapter. The descriptions are qualitative and are intended for architects and others not trained in structural dynamics or earthquake engineering. The principles that govern the interaction between the ground and building components are described and explained using both technical and layman's terms. Throughout the discussion a common idea prevails: as the motions of an earthquake travel from their source to the site, then to the building, and finally to individual building components, they are constantly being modified. The ground motions at a site are different from what they were when they first emanated from the source; the response motions of the building are different from the input ground motions; and the response motions of individual components are different from the input motions of the building as a whole.

THE EARTHQUAKE PHENOMENON



Earthquakes release energy which emanates from a fault as stress waves. These waves cause rock and soils to displace, creating three-dimensional vibratory motions. Each ground particle activates the next particle in a pattern similar to the movement of sound and light waves. As the stress waves pass through a particular location, they force the soils and rock to vibrate, and at the surface the waves are perceived as the ground shaking known as an earthquake. Ground shaking is the three-dimensional movement of a particular point on the ground surface and can be represented by the six standard orthogonal components of motion, three translations and three rotations. Of these, the three translational components are generally considered to be most significant and they are the only ones recorded by strong motion instrumentation.

fault trace

hypocenter or focus

epicenter

Earthquakes are caused by movements of the earth's crust over time. Energy is stored and then released by a sudden displacement of one earth section with respect to another. Ground displacement is often caused by a sudden shearing action along a fault, which is the plane of intersection between adjacent tectonic plates located under the continents and oceans. Fault planes beneath the ground often extend to the surface, where displacements occur along the fault trace. The geometric center of the movement, which is the true center of the earthquake, may be as deep as 700 km and is called the hypocenter or focus. The geographical location of the center of movement at the ground surface above the hypocenter is called the epicenter.

Richter Magnitude

energy released (ergs)

The amount of energy released at the hypocenter is called the earthquake's magnitude, and is usually measured on the Richter Scale. On this scale 4.0 does not represent twice as much energy released as 2.0; rather, the scale is a function of a logarithmic equation, $\log E = 11.8 + 1.5M$, which results in a 32-fold increase in the energy released for each unit increase in Richter magnitude:

Richter Magnitude	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
Energy Released (ergs)	6.3×10^{14}	2.0×10^{16}	6.3×10^{17}	2.0×10^{19}	6.3×10^{20}	2.0×10^{22}	6.3×10^{23}	2.0×10^{25}

Roughly speaking, earthquakes below a Richter magnitude of 3.0 are minor, those from 4.0 to 5.0 are moderate, and those above 6.0 are severe. For example, the 1906 San Francisco earthquake has been estimated to have had a magnitude of 8.3, the 1940 El Centro earthquake was recorded to be 7.1, the 1964 Alaska earthquake to be 8.4, and the 1971 San Fernando earthquake to be 6.6. All of these earthquakes were severe. The mightiest earthquake ever recorded had a magnitude estimated to have been 8.9 and occurred in Columbia, Ecuador in 1906.

Richter magnitudes measure only the energy released at the source, which is not necessarily related to the earthquake's destructiveness. If the epicenter is located a very large distance from an inhabited area, then even large amounts of released energy may not cause any damage to man-made structures. For earthquakes whose epicenters are close enough to inhabited areas to cause damage, the amount of damage will vary from one place to another. Damage is sometimes worse at distances further from the epicenter than at locations closer to it, for reasons that will be explained later in this chapter. Consequently, intensity, a qualitative term, is used to describe local destructiveness. One earthquake will have a single magnitude, but its intensity will vary from location to location, corresponding to its degree of destructiveness.

intensity

Energy released from an earthquake emanates from the fault as low and high frequency stress waves. These waves produce motions of the ground particles which are oscillatory, or vibratory, in nature. The motions are not regular or repetitive, like the motions of a single pendulum. However, even though the motions are highly irregular, they can be thought of as being a sum of a series of repetitive or periodic motions. These periodic motions, or harmonics, are described by their frequency or period, and by their amplitude. Frequency is the number of cycles per second of the particular harmonic. Period is the inverse of frequency and is expressed in terms of number of seconds per cycle. Amplitude is the measure or extent of the acceleration, velocity, or displacement of each harmonic.

harmonics

frequency

period

amplitude

frequency content

In this report, the term frequency content is sometimes used to describe the frequencies which are predominant in ground motions. This term is useful in some cases to distinguish between motions that contain predominantly high frequencies or predominantly low frequencies. In general, ground motions with a high frequency content may adversely affect short, stiff buildings, while ground motions with a low frequency content may adversely affect taller, flexible buildings.

Unless otherwise defined, reference to amplitude refers to acceleration, because it is commonly recorded and is a significant characteristic used to determine earthquake stresses caused in buildings. Acceleration is often described as a percentage of the acceleration of gravity, 32 ft/sec/sec; thus an earthquake with a peak amplitude of 0.25g refers to

Acceleration is often described as a percentage of gravity, g.

ground particle vibrations with a peak acceleration of 8 ft/sec/sec. Ground shaking accelerations vary up to 0.1g for what might be termed a minor earthquake, from 0.2g to 0.3g for a moderate earthquake, and greater than 0.4g for a severe earthquake. Examples presented in this chapter illustrate recorded acceleration time histories in recent earthquakes. Accelerations slightly over 1.0g were measured close to the epicenter during the 1971 San Fernando earthquake.

As waves travel through the earth's crust their frequencies and amplitudes are filtered and modified.

The characteristics of stress waves are dependent upon the nature of the earthquake source: the depth, the length of the movement along a fault, geological formation, and other physical ground properties. Waves of varying characteristics emanate from a fault resulting in a superimposition of a series of different waves with various frequencies and amplitudes. As these waves travel through the earth's crust, they are reflected and refracted by geological formations and the ground surface in a complicated manner. In this process, energy is dissipated and the characteristics of the waves are modified. This effect may be thought of as filtering: as the waves move out from the fault they reach a particular site with modified amplitudes and frequencies; therefore, ground motions at a distance from a fault do not have the same characteristics as at the source. For example, in the 1964 Alaska earthquake the higher frequencies were filtered out as they traveled long distances to Anchorage, Alaska; as a result waves of very low frequencies reached that area.

accelerogram

The ground motions caused by the movement of stress waves through the ground are three-dimensional. Figure 1-1 shows the horizontal and vertical components of the three-dimensional motions of a ground particle. The frequencies and accelerations of ground motions at a particular location are plotted on a time history record called an accelerogram. The motions are recorded for the duration of an earthquake by an instrument which measures acceleration in the three orthogonal directions. Figure 1-2 shows an accelerogram from the 1940 El Centro earthquake. This particular record indicates that the peak ground acceleration along the north-south axis is equal to approximately 0.30g. Motions along the east-west and vertical axes were recorded on other accelerograms and showed similar motion characteristics. Velocities and ground displacements can also be plotted in the form of time history records.

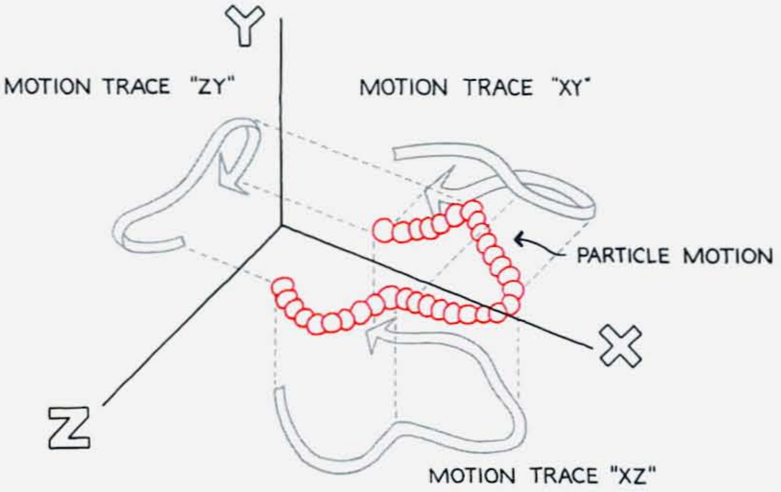


FIGURE 1-1. HORIZONTAL AND VERTICAL TRACES OF THE PARTIAL MOTION OF AN EARTH PARTICLE DURING AN EARTHQUAKE.

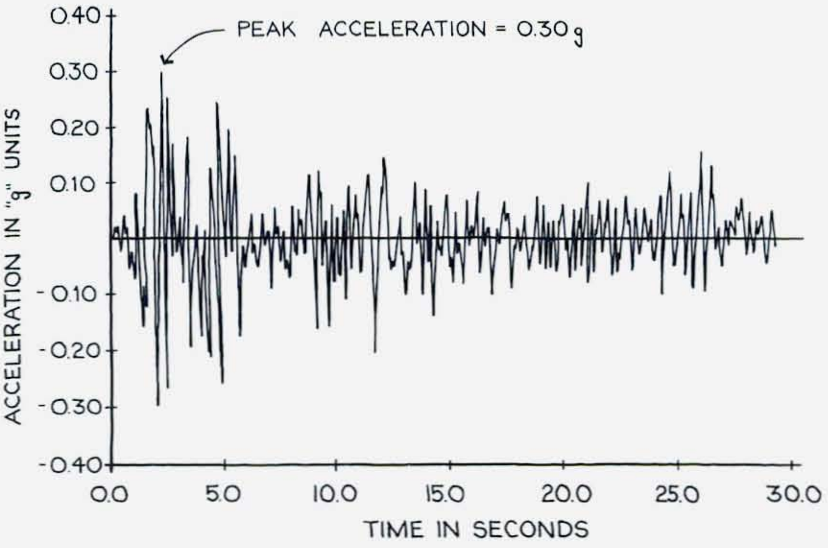


FIGURE 1-2. ACCELEROGRAM OF THE 1940 EL CENTRO EARTHQUAKE, NORTH-SOUTH PROJECTION OF ACCELERATION.

levels of earthquake for design

Based upon the history of earthquake faults and knowledge of the earth's physical properties, seismologists can predict on a probabilistic basis the likelihood of the occurrence of earthquakes of various magnitudes for a future period of time. In the development of design criteria, two levels of earthquakes are typically estimated for a particular building site: a very severe earthquake which buildings are designed to sustain with significant damage, but without collapse, and a lesser one which buildings are designed to endure without significant damage. This concept will be described in greater detail in Chapter Two.

SITE RESPONSE

As stress waves pass through a particular location, they activate the bedrock and overlying layers of soils, forcing them to vibrate. This vibratory response of the layers of soil at a site to input motions is called the characteristic site response. The site response at ground level is dependent upon both the characteristics of the input motions at the bedrock level and the physical properties of the site itself. A site can be thought of as being supported by a geological structure; that structure has its own dynamic characteristics that will cause the site to respond differently from other sites given the same input motions. The dynamic characteristics of a site are determined by the physical properties of its geological structure, which consists of various layers of soil and rock over bedrock. The configuration of the site materials, the form of the bedrock, the vertical and horizontal dimensions of the overlying soil deposits, the angle of orientation of the bedding planes, and the mass, stiffness, and damping characteristics of the various materials all affect the dynamic characteristics of the site. The critical parameters of site response are the periods of vibration of the surficial layers of soil and the energy dissipating characteristics of the soil. Fundamental (lowest) periods of vibration for sites roughly vary from about 0.10 seconds for stiff sites to 5.0 seconds for very flexible sites, with the range of 0.25 to 1.0 seconds being typical. Temporary displacements of the ground surface during vibratory motions vary from only fractions of an inch up to 5 to 10 inches for a severe earthquake.

geological soil structure

The layers of soil beneath a site act as a filter for the input motions at bedrock, causing some frequencies to be amplified and others to be attenuated.

The layers of soil beneath a site act as a filter for the input motions at bedrock, causing certain frequencies of motion to be amplified and other frequencies to be attenuated. The degree of amplification or attenuation is related to the relationship between the frequencies of the while other buildings receive input motions from a first or basement floor and basement walls in contact with the ground. The parts of the building above the ground form a vertical structure supported at the base. When the base is set in motion, the rest of the building is forced to move and responds with vibratory motions. The characteristics of building shaking during an earthquake are known as the building response and are normally described in terms of acceleration, velocity, displacement, or other engineering parameters.

building response

Both vertical and horizontal components of input and response motions are important. The effect of the vertical components of motions is to first increase and then decrease the effects of gravity. When the ground acceleration is upward, the vertical component adds to the effects of gravity, and vice versa. Horizontal elements such as floors and ceilings may deflect up and down. The effect of horizontal components of motions is to shift the building parts horizontally with respect to each other. The bases of columns move laterally with respect to the tops, and different floor levels of the building move horizontally with respect to each other.

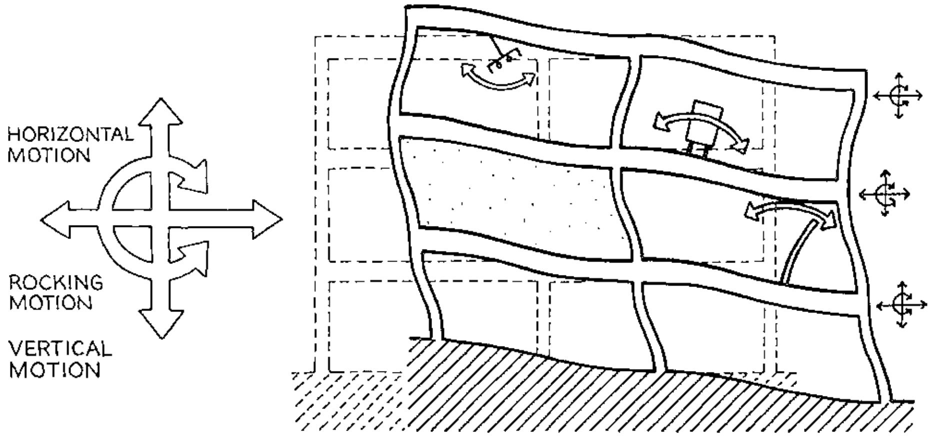


FIGURE 1-5. PATTERNS OF RESPONSE IN A BUILDING: CHANGING DIRECTIONS, ACCELERATIONS, AND DISPLACEMENTS.

The patterns of response are such that one portion of the building changes direction before another causing different parts of the building to be moving simultaneously in different directions with different accelerations.

Individual parts of the building exhibit both translational and rotational displacements with respect to one another. The patterns of response of the building are such that one portion of the building changes direction before another, causing different parts of the building to be moving simultaneously in different directions with different accelerations (Figure 1-5). Depending upon the frequency of the input motions and the physical properties of the building, each component will have its own accelerations, displacements, and frequencies during the earthquake.

The Response Spectrum

The concept most often used to represent important characteristics of earthquakes is the response spectrum. This concept will be used here to explain the dynamic behavior of buildings as a whole; later it will be used to describe the dynamic behavior of the individual components of the building. When architects work with structural engineers on the design of a building, the response of proposed building design alternatives is a major concern. The architects and engineers must coordinate architectural design and engineering design such that the final product will be a building with an acceptable response during an earthquake. Engineers use the response spectrum as a means of estimating the potential response of the various design alternatives. By understanding the concept of the response spectrum, architects can better communicate with their engineers in achieving the desired architectural features and an acceptable response to earthquake input motions. In addition, the dynamic principles upon which the response spectrum is based are useful in explaining further the nature of a building's motions during earthquakes.

SDOF:

mass (M)
stiffness (K)
damping dashpot (C)

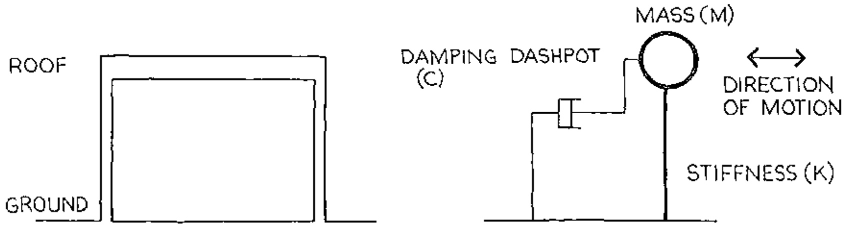
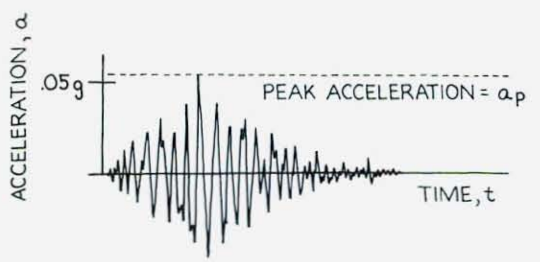


FIGURE 1-6. SINGLE STORY STRUCTURE AND ITS CORRESPONDING SINGLE DEGREE OF FREEDOM MODEL (SDOF).

procedure for developing response spectra

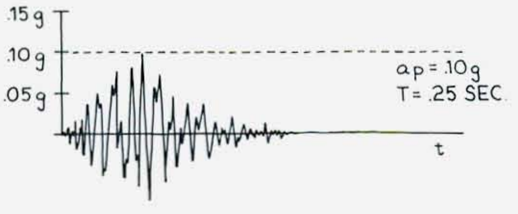
Response spectra are developed according to the following procedure. Imagine a simple single story building which can be modeled for dynamic analysis reasons by the diagram shown in Figure 1-6, which is called a single degree of freedom model (SDOF). A single degree of freedom represents one direction of motion for a single mass, as shown in the diagram. The mass on the model (M) represents the



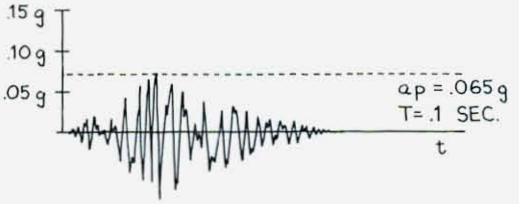
GROUND INPUT MOTION FOR ALL BUILDINGS

PERIOD CALCULATED FROM $T = 2\pi\sqrt{K/M}$

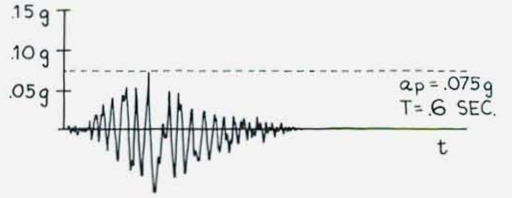
TIME HISTORIES OF RESPONSE:



RESPONSE OF BUILDING #1

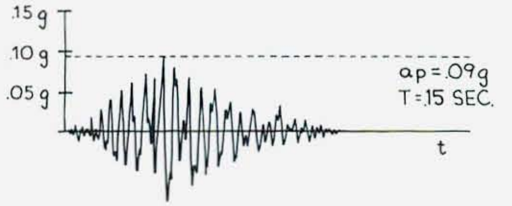


RESPONSE OF BUILDING #2



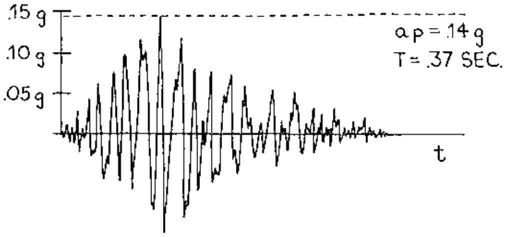
RESPONSE OF BUILDING #3

RESPONSE OF BUILDING #4

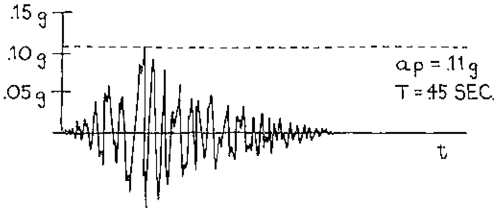


RESPONSE OF BUILDING #5

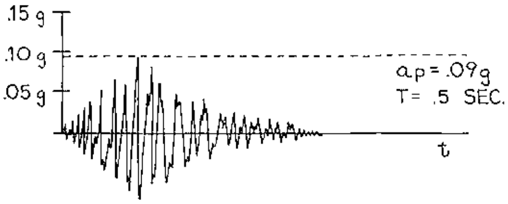
FIGURE 1-7. EXAMPLE ILLUSTRATING HOW A RESPONSE SPECTRUM IS DEVELOPED.



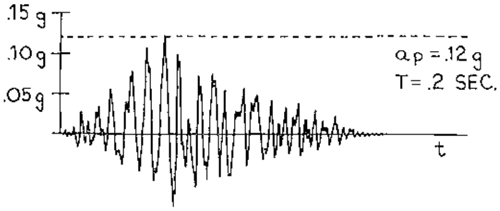
RESPONSE OF BUILDING #6



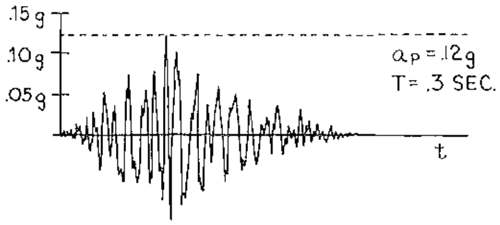
RESPONSE OF BUILDING #7



RESPONSE OF BUILDING #8



RESPONSE OF BUILDING #9

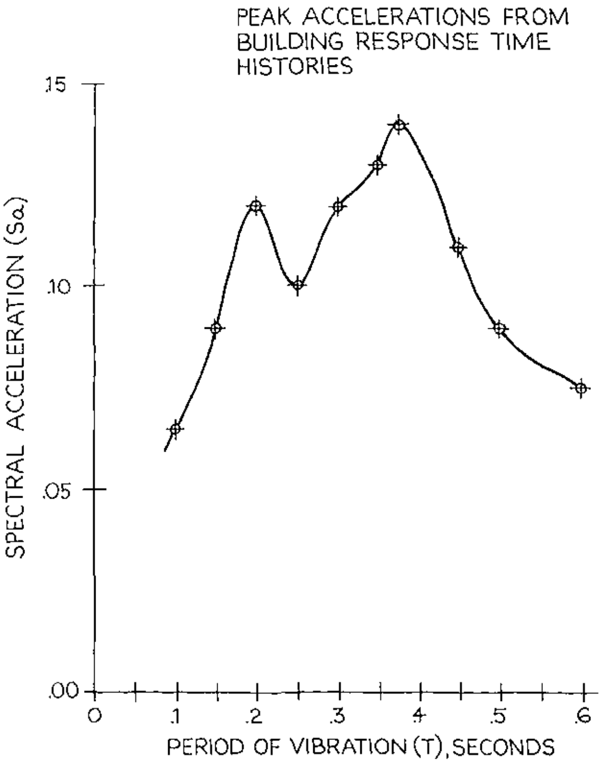


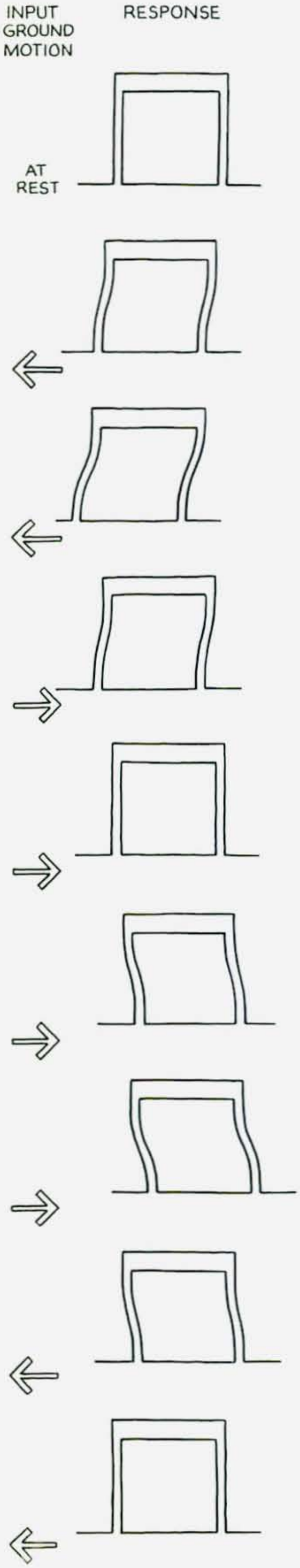
RESPONSE OF BUILDING #10

:

RESPONSE OF N^{TH} BUILDING

RESPONSE SPECTRUM





weight of the roof and walls, the vertical column represents the stiffness (K) of the walls, and the third element, called a damping dashpot (C), represents the inherent ability of the building to dissipate energy (damping) and thereby slow any vibratory motions to which the building might be subjected. The damping dashpot is analagous to a shock absorber in an automobile.

If one considers a large number of such single story buildings represented by their models, each having different mass and stiffness, and all subjected to the same earthquake input motions, or "input" time histories (shown as a graph of acceleration versus time), then each building will have its own response to those input motions (Figure 1-7). The building's deflections due to its response to the input motions are shown for various points in time in the margin. The period of vibration of each building can be calculated from the equation $T = 2\pi\sqrt{M/K}$. A peak or maximum acceleration and the period of vibration can be calculated for each building. If one then graphs each building's (or SDOF's) peak acceleration with its corresponding period of vibration, the result is a response spectrum for the given earthquake input motions. On the response spectrum the plotted peak accelerations are also known as spectral accelerations.

Thus, the response spectrum represents the responses of many buildings or many SDOF's having different periods of vibration and different peak accelerations. If one designs a one-story building for a particular site that will have certain input motions for a given earthquake, one can use the response spectrum to estimate the response of various building design proposals. A given design can be analyzed by structural engineers to determine the proposed building's period of vibration. Using this period and an assumed damping value, one can then determine the corresponding acceleration on the response spectrum for the earthquake input motion at the proposed site. Knowing the acceleration, one can multiply it by the weight of the roof of the one story building to determine the shear forces in the columns and walls. The building design can then be checked to determine its ability to endure these forces.

The above procedure using the response spectrum for design applies only if the mass of the system is concentrated at a single point, in this case the roof of the one story building. If there is more than one story, the use of the response spectrum for design is somewhat more complicated. In other than a single story structure the mass of the system will be concentrated at several floor levels, and the building would be represented by a multiple degree of freedom (MDOF) model. There will as many different patterns of vibration, or modes, with certain shapes and frequencies, as there are floor and roof levels for a building vibrating in one plane. Both planes of the building must be analyzed, but for simplicity in this discussion each floor level is assumed to be subject to lateral displacements only in the plane of the paper. A building's response will include several higher modes (2nd, 3rd, 4th, 5th, and so forth). The first or fundamental mode contributes approximately sixty to eighty percent of the total building response, while higher modes have successively less influence. The term predominant modes refers to those modes that have the greatest influence on building response.

modes

The fundamental mode contributes sixty to eighty percent of the total building response.

predominant modes

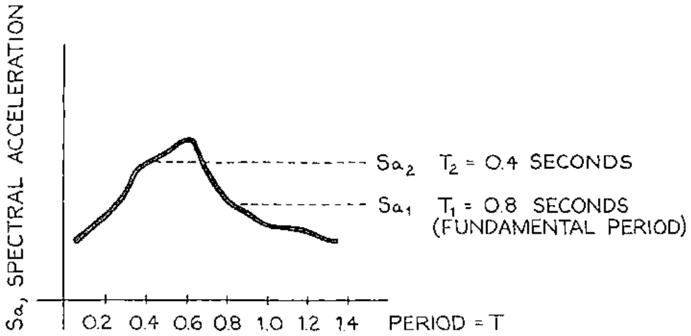
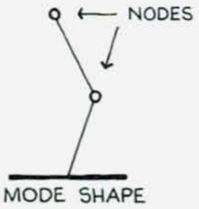


FIGURE 1-8. SPECTRAL ACCELERATIONS AND CORRESPONDING PERIODS FOR FIRST AND SECOND MODES OF A TWO STORY BUILDING.

Each mode of a building will have a corresponding period of vibration, T, which can be calculated. The building's first mode will have the longest period. Using the building's periods, one can find the corresponding spectral accelerations for each of its modes on the response spectrum for the site's input motions. Figure 1-8 shows this procedure for a two story building. Then using the spectral acceleration for each mode, a participation factor, and a factor describing the mode shape, the displacement *node*



for each node of a mode can be calculated. A node corresponds to the location of the mass at each floor level; hence, a two story structure will have two nodes. Once the displacement for each node in each of the modes has been calculated, the mode shapes with their displacements are combined to produce the total response of the building in terms of displacements, shown in Figure 1-9. A similar procedure is used to obtain the maximum total moments, shears, and so forth, for the building. This procedure is known as the response spectrum method for calculating seismic response. There is also a time-history method which is sometimes used. Both methods are described in more detail in Appendix B.

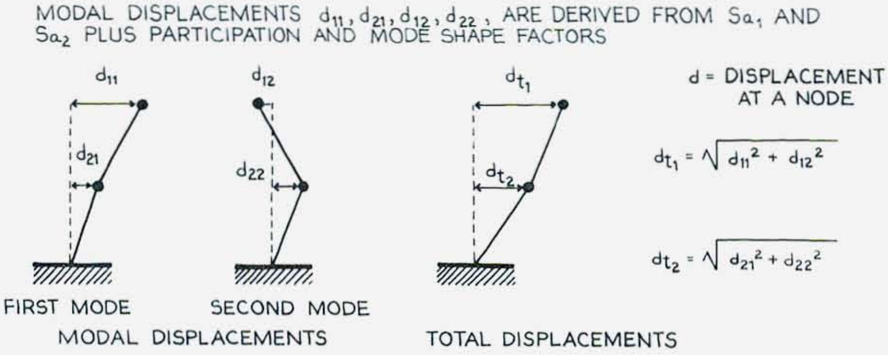


FIGURE 1-9. MODAL DISPLACEMENTS COMBINED TO PRODUCE TOTAL DISPLACEMENT FOR A TWO STORY BUILDING.

Response of Buildings to Input Ground Motions: Amplification and Attenuation of Frequencies

During an earthquake a building will generally have accelerations and displacements that are smaller or greater than the input motions of the ground. Recall from the previous descriptions of site response that the factors that determine response of a site to bedrock motions are related to the correspondence of the frequencies of input motions to the frequency of the soil layers; damping characteristics also affect site response. These factors are also applicable to the relationship between input ground motions and building response.

The correspondence between the frequencies of the ground input motions and the frequencies of the structure is sometimes a significant factor in determining building response.

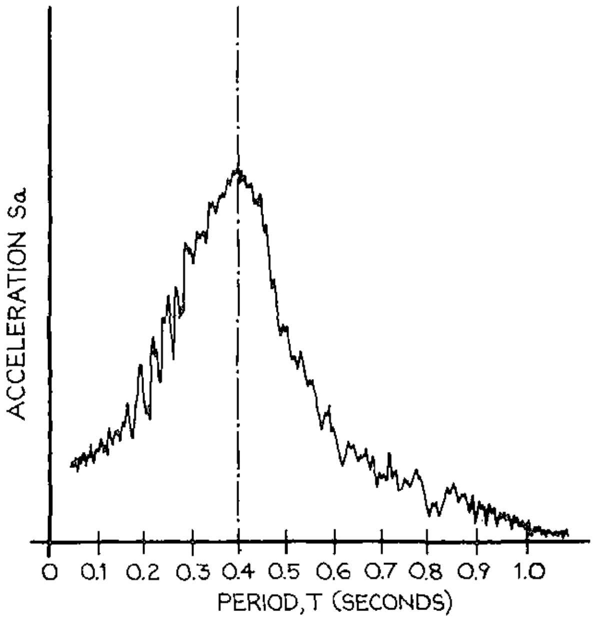


FIGURE 1-10. HYPOTHETICAL RESPONSE SPECTRUM ILLUSTRATING THE DEGREE OF AMPLIFICATION OF ACCELERATION FOR BUILDINGS OF DIFFERENT PERIODS OF VIBRATION.

Figure 1-10 shows a hypothetical response spectrum with acceleration peaking at about 0.4 seconds. For buildings with periods to the far right side of the response spectrum, the building will experience large displacements relative to the ground at relatively small accelerations (that is, the building is quite flexible). The displacements of the input ground motions are amplified but the accelerations are smaller. For buildings with periods on the far left side of the response spectrum, the building will experience about the same accelerations as those of the input ground motions, and will also experience very small displacements relative to the ground (that is, the building is quite stiff). In the region where the period is equal to about 0.4 seconds, the period of the building corresponds approximately to the period of the input ground motions. The result of this correspondence of periods is a high amplification of accelerations, or pseudo-resonant state, and some displacement of the building relative to the ground. The relative displacements and accelerations of each of these hypothetical cases are shown in Figure 1-11. Buildings tend to act in a manner closer to the pseudo-resonance condition than they do to the other extreme conditions. Certain frequencies are attenuated and others amplified; the result of the interaction of the input ground motions with buildings is almost always some degree of amplification of the input motions. Thus, in general, the effects of site conditions are potentially the most severe when the predominant periods of the building structure coincide with the predominant periods of the ground. Although there is some uncertainty in the prediction of building periods and considerable uncertainty in the calculation of the periods of soil deposits, the general principle holds true. Example No. 1 of Appendix A illustrates in more detail the influence of site conditions on the response of a building.

The effects of site conditions are potentially most severe when the predominant periods of the input ground motions and the building coincide.

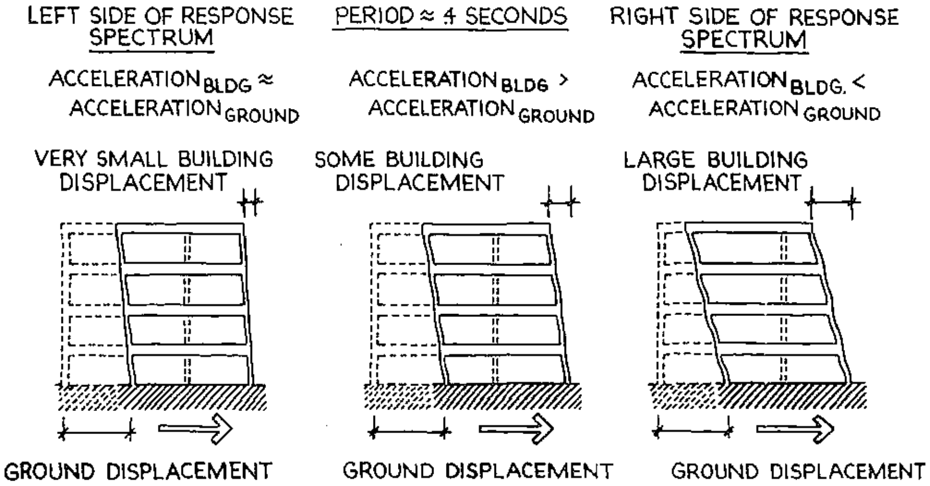
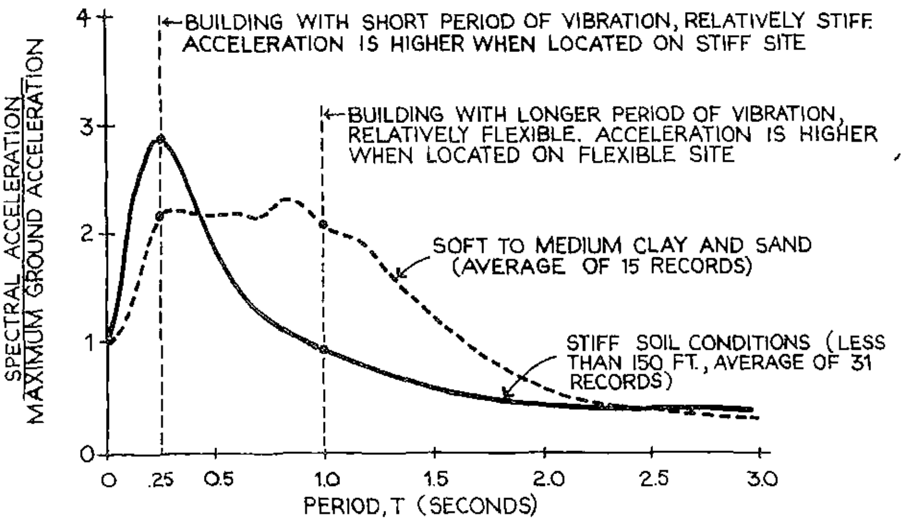


FIGURE 1-11. COMPARISON OF RELATIVE DISPLACEMENTS AND ACCELERATIONS FOR HYPOTHETICAL BUILDINGS AT DIFFERENT POINTS ON THE RESPONSE SPECTRUM IN FIGURE 1-10.

As a qualitative example of the possible effects of the correspondence of input ground motion frequencies and building frequencies, consider Figure 1-12, where a number of response spectra have been combined to produce average acceleration spectra for flexible and stiff site conditions. A building with a relatively long period of about one second on a soft to medium clay and sand site (relatively flexible) may experience motions twice those that it would experience if it were on a stiff soil site. On the other hand, a building with a relatively short period of about 0.25 seconds may be subjected to higher motions than if the same structure were located on a flexible site.



AVERAGE ACCELERATION SPECTRA FOR 5% DAMPING

FIGURE 1-12. EXAMPLE OF APPROXIMATE EFFECT OF DIFFERENT SITE CONDITIONS ON STIFF AND FLEXIBLE BUILDINGS.

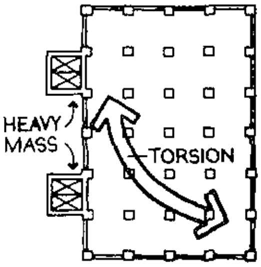
The Effects of a Building's Dynamic Characteristics on Its Response

dynamic characteristics

When a building responds to input ground motions, its dynamic characteristics are as much a factor in determining that response as the dynamic properties of the input motions. A building's dynamic characteristics are related to its motions during hypothetical free response, that is, when it is deflected, released, and allowed to oscillate freely without additional external forces. The free response dynamic characteristics of a building consist of its frequencies, mode shapes, and damping during free vibration. The importance of the relationship of the frequencies of input ground motions to the frequencies of the building has been discussed above. The modes of vibration of the building and their corresponding frequencies critically influence response. The predominant modes are the most important: the fundamental (first) mode of vibration is most often the controlling one, but other predominant modes can also have significant effects on building response. The building's inherent ability to damp its response (dissipate energy) can also be a key factor in affecting the tendency toward amplification or attenuation of the input ground motions. Control of the dynamic characteristics of the building is *physical properties*

achieved by manipulating the building's physical properties: generally, its mass, stiffness, and damping. The ways in which these properties affect dynamic characteristics of the building and ultimately the building's response are discussed below.

Mass: Recalling the equation for the period of a single story building (or a SDOF system), $T = 2\pi\sqrt{M/K}$, one can readily see that a building's periods are particularly dependent upon its mass. Altering the mass of the building will alter its period. If altering the mass makes the predominant periods of the building closer to the predominant periods of the input motions, then the building's response may be amplified.



The distribution of mass within the building also has important effects on response. Uneven and assymmetrical distributions of mass in a building will cause the building to respond with motions that include torsion as well as translation.

material stiffness

configuration

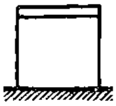
connections between components

Stiffness: Again examining the equation for the period of a single story building, $T = 2\pi\sqrt{M/K}$, one observes that the stiffness factor, K, will influence the period of the building; hence, stiffness will directly influence the degree of amplification of input ground motions. The stiffness factor K represents the stiffness of the vertical building components (walls and columns) between the concentrated mass (M) of the building at the floors. A building's overall stiffness is dependent upon the material stiffness of its components; its configuration -- number of stories, general form in plan and section, geometry of various systems and components; and the types of connections between the components. Because various parts of a building are stiffer than others, a building will exhibit motions that include torsional as well as translational displacements.

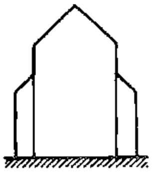
There is no inherent advantage or disadvantage to stiff or flexible buildings.

Currently there are no accepted classifications of buildings or more precise terminology to describe attributes of building response related to stiffness. A somewhat loose distinction between "flexible" and "stiff" is the only basis for describing the general differences in build-

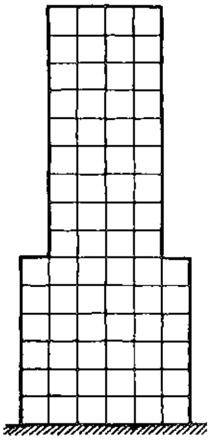
1. $T \leq 0.05$ SEC. $f > 20$ CPS



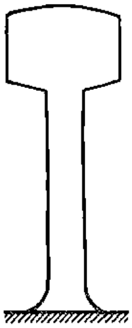
2. $T = 0.1$ SEC. $f = 10$ CPS



3. $T = 0.4$ SEC. $f = 2.5$ CPS



4. 15 STORY $T = 1$ SEC., $f = 1$ CPS
5. 40 STORY $T = 2.5$ SEC., $f = 0.4$ CPS



6. $T = 4$ SEC. $f = 0.25$ CPS

Diagrams from Robert L. Wiegel, ed., Earthquake Engineering (Englewood Cliffs, N.J.: Prentice-Hall, 1970), p. 404.

ing response. There is no inherent advantage or disadvantage to stiff or flexible buildings. The motions of either type of building can be amplified if the building's frequencies correspond to the frequencies of the input ground motions. Both relatively stiff and relatively flexible buildings can be susceptible to high amplification of accelerations. But for a given level of acceleration, a relatively stiff building will deflect less, and thus have smaller displacements and deformations than would a flexible building.

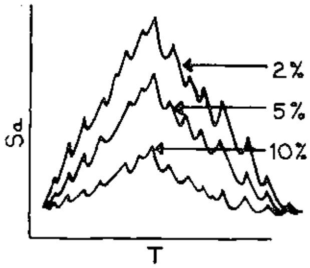
Most low-rise buildings tend to be relatively stiff, while high-rise buildings tend to be relatively flexible. Long span moment resisting frame buildings tend to be quite flexible, while braced frame, shear wall, shell, and monocoque frame buildings tend to be quite stiff. In general stiff buildings have short fundamental periods of vibration, while flexible buildings have longer fundamental periods; however, there is a wide range of magnitudes of periods depending upon the configuration of the building, the stiffness of materials, and the types of connections between components. For example, three story masonry bearing wall buildings are relatively stiff and may have fundamental periods as low as 0.2 seconds, while three story long span moment resisting frame buildings may have periods of over 1.0 seconds. On the other hand, a ten story shear wall or braced frame building might be considered relatively stiff for its height and have a period of 1.0 seconds, while a ten story long span moment resisting frame building might have a period as long as 2.0 seconds and be considered relatively flexible.

Damping: The damping property of a building is related to the degree to which a building will dissipate energy (input motions) through conversion to heat, including molecular transfer and friction effects. Damping is the measure of the building's resistance to continued vibration, and is determined by all of the building's systems, materials, and finishes. Damping is described by a damping coefficient, which is the fraction of the critical damping, the force required to stop a freely vibrating system in one cycle. The damping coefficient is commonly expressed in a percentage form. In most buildings the damping coeffi-

Buildings with many finishes and substructures tend to have higher damping coefficients.

cient generally ranges from 2 percent to 10 percent. Buildings with many finishes and substructures, such as partitions and ceilings, tend to have higher damping coefficients than do buildings with fewer components. Damping is a major factor in determining the response of a building, because, when a building damps its vibrations due to input ground motions, the amount of amplification of those input motions will be decreased. Damping coefficients are utilized to produce different response spectra for the design of a building on a particular site. The higher the damping coefficient a building has, the smaller will be the accelerations for which the building must be designed.

damping coefficient



Nonlinear Response

In the above discussion of the response of single and multiple degree of freedom systems, of dynamic characteristics of response, and of the physical properties of materials, the assumption has been that the building is responding in the linear range, which is usually not the case for very severe earthquake motions. In the non-linear range the deformations of the various members of the structure exceed the elastic capacity of the members, thus causing yielding or permanent deformations. Special analysis techniques must be used to account for the non-linear force deformation characteristics of yielding members.

For large deflections building response becomes non-linear and the apparent periods of vibration become longer.

Within the linear elastic range, the periods of vibration that a building has are the same regardless of how much the building is deflected; however, for large deflections the response becomes non-linear and the apparent periods of vibration become longer. The response becomes non-linear because of changes in the stiffness and damping characteristics of the building. Connections that are initially tight will tend to loosen during an earthquake; as a result the stiffness will tend to decrease and the damping coefficient will tend to increase. This non-linear effect is important to the designer because it means that building response is also affected by the severity of input ground motions: if the physical properties of the building change, so will the dynamic characteristics of the building, thus affecting the response of the building to input motions.

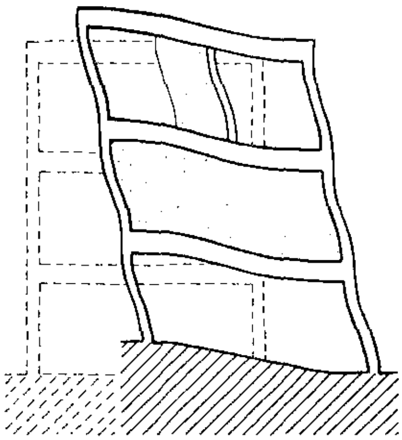


FIGURE 1-13. CHANGED SHAPE OF COMPONENTS DUE TO RELATIVE DISPLACEMENT.

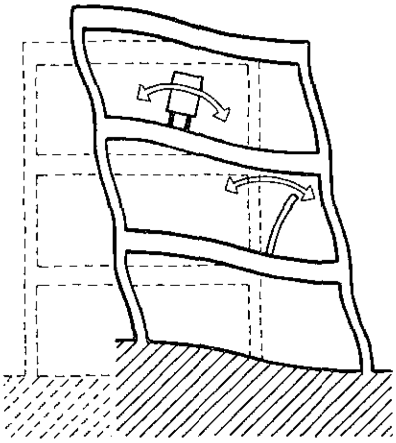


FIGURE 1-14. COMPONENTS SUBJECT TO VIBRATIONAL EFFECTS.

PATTERNS OF BUILDING RESPONSE - THE DYNAMIC ENVIRONMENT

The response of a building as a whole consists of a changing pattern of spatial and geometric relationships between the various floors of a building, and between its various component parts. At any particular location, the response may be described by the frequencies of the motions, the peak accelerations, and the associated peak displacements. These peak amplitudes occur in different parts of the building at different times. Of key importance to designers when considering the motions of the building are the forces in various components, which are caused by the accelerations of their vibratory motions, and the relative displacements, which are caused by differential movements of various parts of the building with respect to each other at each point in time. Each component or system of components has its own Dynamic Environment, consisting of the relative displacement and vibrational effects of the portion of the building in which the component is located. Relative displacements of a building are due to the deformation of the building as a whole, which results in forced changes in the relationships or shapes of the various components in the building. An example of a component that may change shape due to the deformation of the building is a wall set within a structural frame, as shown in Figure 1-13. Vibrational effects are those effects on a component caused by the component's response to input motions from the particular part of the building with which it comes in contact or to which it is connected. Examples of com-

Dynamic Environment

relative displacement effects

vibrational effects

ponents subject to vibrational effects are partial height partitions and mechanical equipment, shown in Figure 1-14. Damage will occur to a component if either relative displacement or vibrational effects subject them to excessive deformations or stresses. The response of a component within a building is analagous to the response of a building on the ground, and the same principles of dynamics apply.

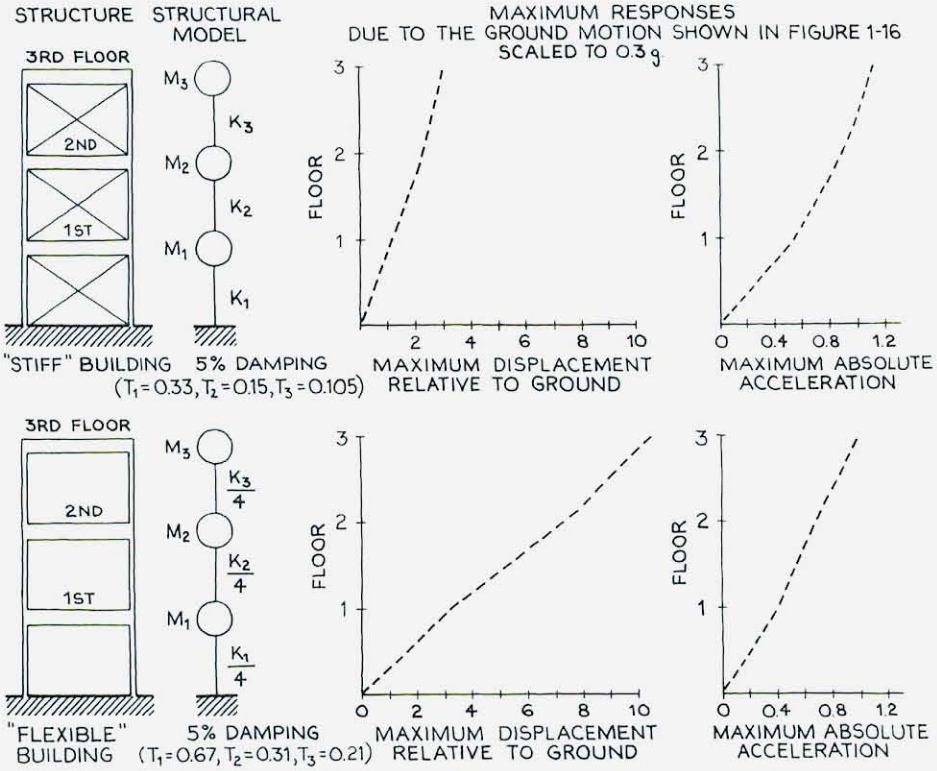


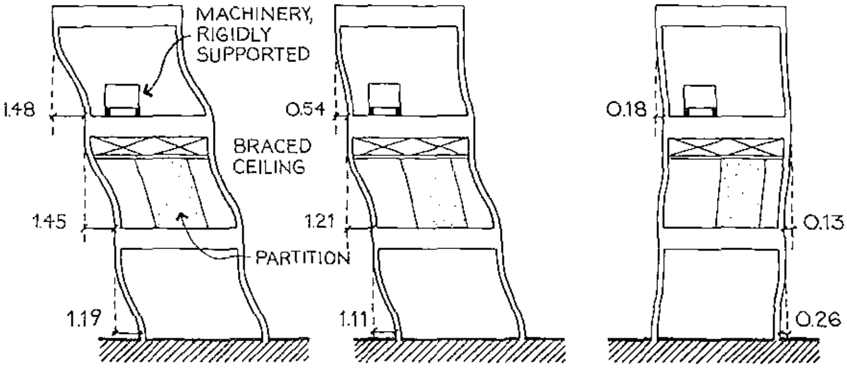
FIGURE 1-15. "STIFF" AND "FLEXIBLE" BUILDINGS AND THEIR MAXIMUM RESPONSES

The differences in the relative magnitudes of accelerations and displacements of Dynamic Environments in "flexible" and "stiff" buildings, and the differences in floor response within the same buildings will be illustrated by the following example involving two different hypothetical buildings. The buildings were modeled and subjected to the artificial time history of ground acceleration shown in Figure 1-16. In response to those input motions, Figure 1-15 shows that maximum floor accelerations of the stiff building (Period = .33 seconds) are slightly greater than those of the flexible building (period = .67 seconds). However, despite the small differences in building acceleration, the maximum floor displacements of the flexible building are three times larger than those of the stiff building. (As a simplification, only building flexural displacements in the plane of the paper are shown.) A comparison of the displacement time histories of the two buildings (Figure 1-17) shows that the cycles of displacement response are noticeably shorter in duration for the stiff building relative to the flexible building, reflecting the differences in the fundamental periods of vibration of each structure. Figure 1-18 illustrates the two buildings' displacements at intervals of 1.0 second. The differences in the relative positions of each floor over time are shown, demonstrating that each component is subject to the pattern of relative displacements of its own Dynamic Environment.

Relative Displacement Effects on Component Response

interstory relative displacements

Relative displacements occur between adjacent buildings, between consecutive floors in a building, and between various enclosure, finish, and service components. Relative displacements between floors are called interstory relative displacements, or, sometimes, interstory drift.



A) TIME: 15.8 SECS. B) TIME: 15.9 SECS. C) TIME: 16.0 SECS.

FIGURE 1-19. HYPOTHETICAL FLEXIBLE BUILDING WITH COMPONENTS SUBJECT TO RELATIVE DISPLACEMENT AND VIBRATIONAL EFFECTS AT SUCCESSIVE POINTS IN TIME.

Figure 1-19 shows the motions of a hypothetical "flexible" building indicating the displacements at successive times. As the building moves in time and deflects relative to its base, the interstory relative displacements change correspondingly. The machinery rigidly supported at the second floor is attached to only one structural component of the building. As a result, this component does not sense the interstory relative displacements caused by the building's

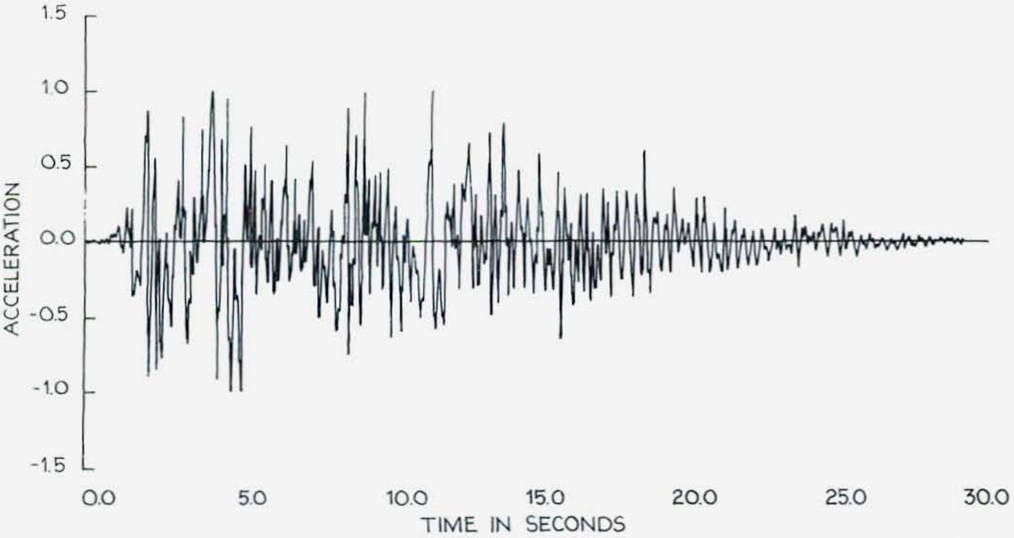


FIGURE 1-16. ARTIFICIAL TIME HISTORY USED AS GROUND MOTION INPUT FOR "STIFF" AND "FLEXIBLE" BUILDINGS OF FIGURE 1-15.

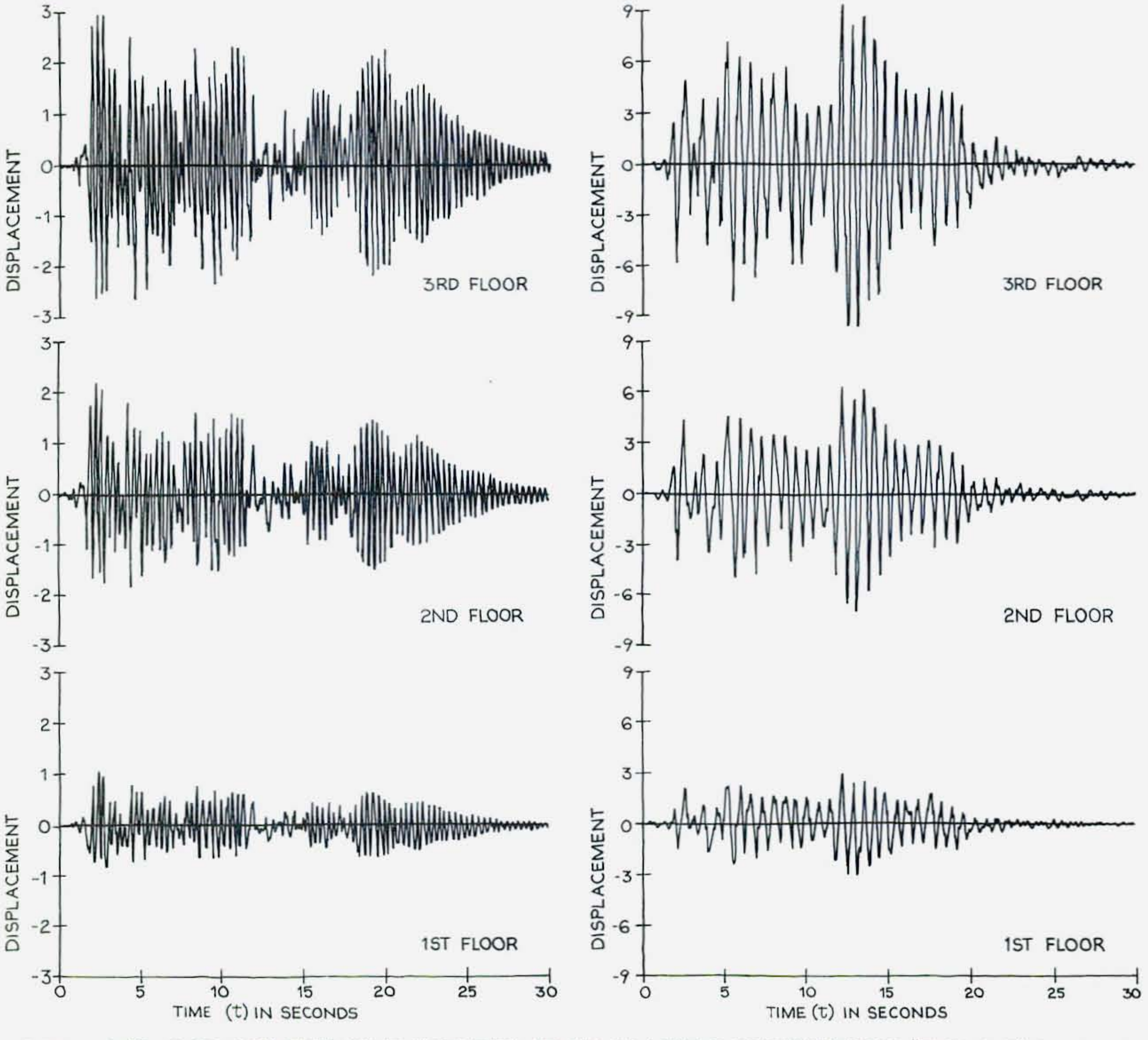
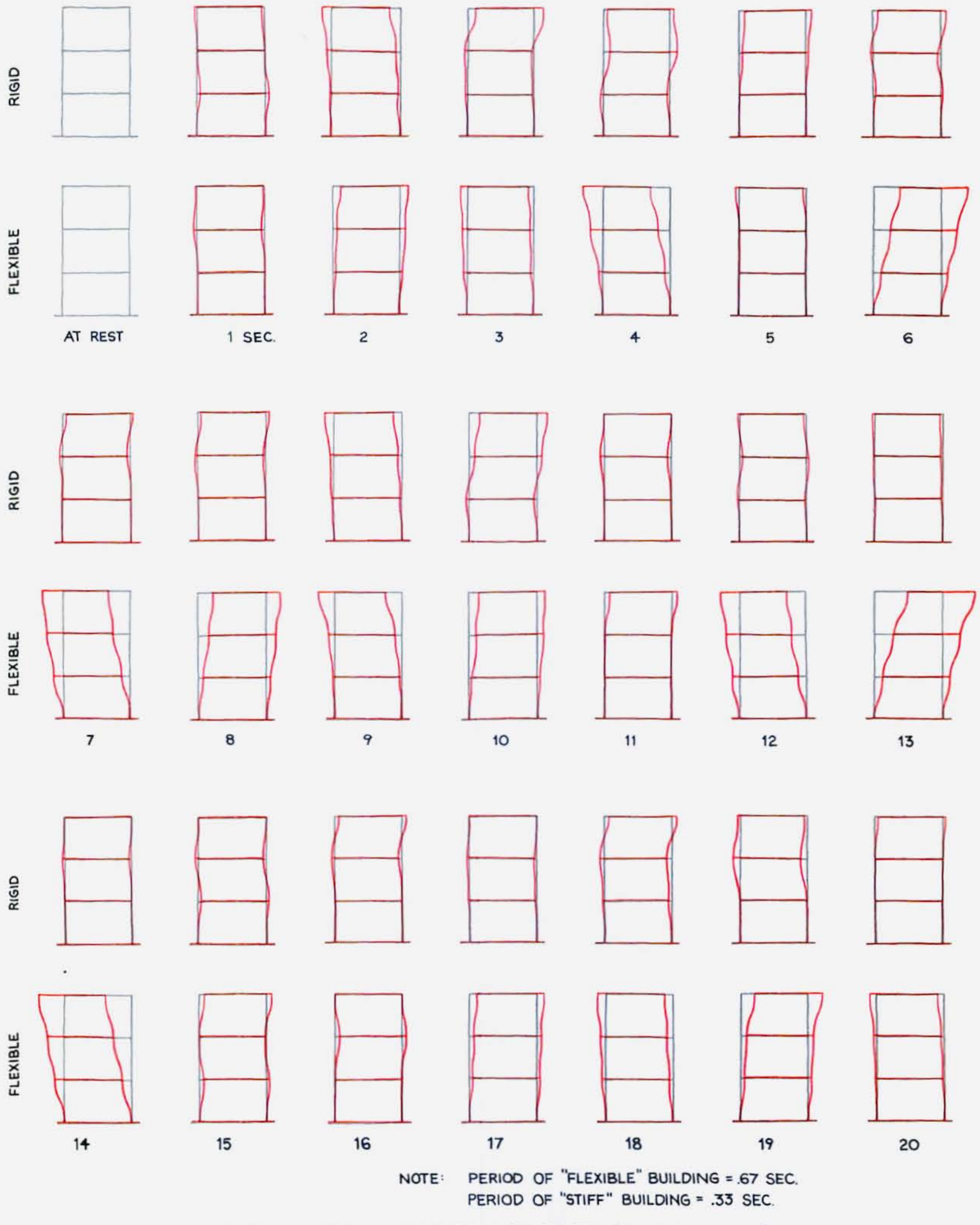


FIGURE 1-17. DISPLACEMENT TIME HISTORIES AT FLOOR LEVELS FOR "STIFF" AND "FLEXIBLE" BUILDINGS.



NOTE: PERIOD OF "FLEXIBLE" BUILDING = .67 SEC.
PERIOD OF "STIFF" BUILDING = .33 SEC.

FIGURE 1-18. COMPARISON OF DISPLACEMENTS (IN ONE PLANE) OF STIFF AND FLEXIBLE BUILDINGS AT INTERVALS OF 1.0 SECOND.

deformations. In contrast, the braced ceiling/partition system located between the first and second floor levels is directly affected by any differential movement between these floors. In general, interstory relative displacements are an important part of the Dynamic Environment for any enclosure, finish, or service component that is attached to two or more structural components.

In general, interstory relative displacements are an important part of the Dynamic Environment for any component that is attached to two or more structural components.

The above example illustrates the concept of interstory relative displacement in the plane of the paper only. Relative displacements, however, are fully three-dimensional and must be visualized as such during the design process. Figure 1-20 shows a three-dimensional representation of a building that is subjected to input motions in two horizontal axes. The response motions of floor level 2 in the x and z axes are shown as graphs of displacement versus time. Point P-2 is initially "at rest" before the earthquake. A similar point P-1 is located on the first floor directly beneath P-2. As the building displaces during an earthquake, the movement of Point P-2 will be in a path as shown in Figure 1-21. The path has an irregular elliptical shape, typical of the paths of most floor motions.

Interstory relative displacement effects can be illustrated in two dimensions by superimposing the paths of reference point P-1 on the first floor and Point P-2 on the second floor as shown in Figure 1-22. The solid line indicates the trace of the motion of point P-1 and the dashed line the motion of point P-2. The differences in displacements between floors at time steps, t_1, t_2, t_3, are indicated by distances Δ_1, Δ_2, and Δ_3, respectively. These are the relative displacements in the horizontal plane which building components, such as braced ceiling/partition systems, must endure. (Vertical relative displacements should also be considered, but for brevity have not been shown here.)

Vibrational Effects on Component Response

Although interstory relative displacements are of no consequence to the machine rigidly supported within the building in Figure 1-19, the machine must be designed for the forces imposed on it due to the acceleration of its sup-

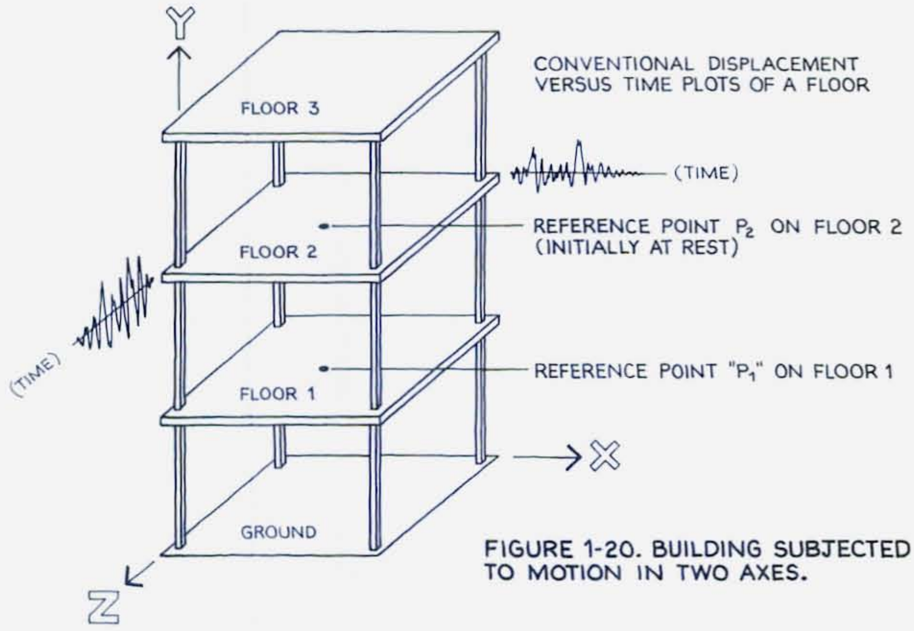


FIGURE 1-20. BUILDING SUBJECTED TO MOTION IN TWO AXES.

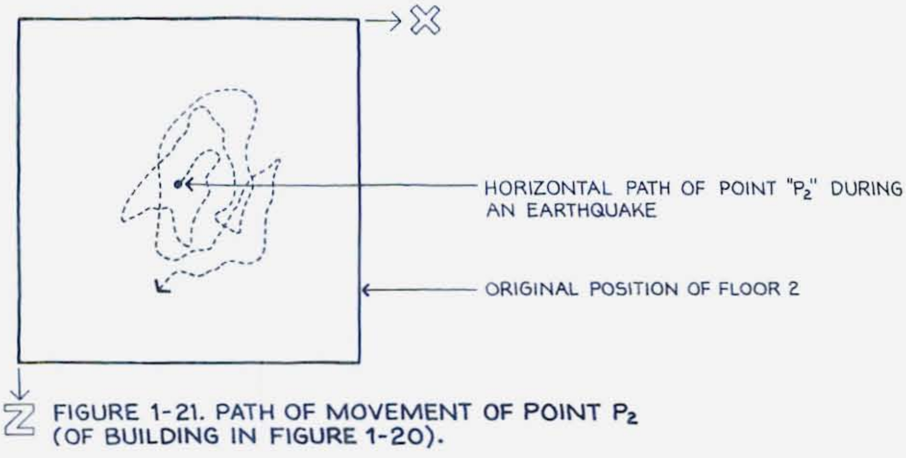


FIGURE 1-21. PATH OF MOVEMENT OF POINT P_2 (OF BUILDING IN FIGURE 1-20).

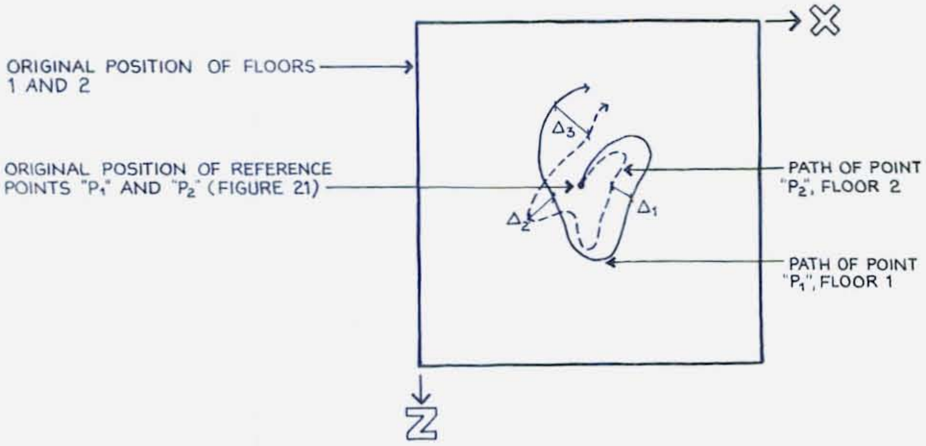


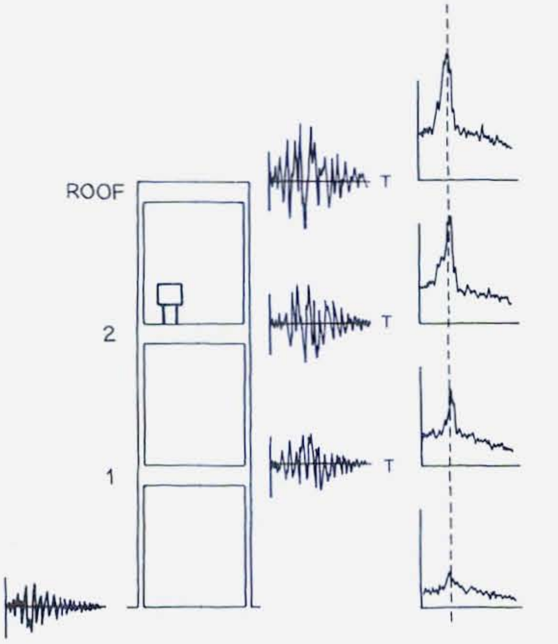
FIGURE 1-22. INTERSTORY RELATIVE DISPLACEMENTS IN HORIZONTAL PLANE BETWEEN FLOORS 1 AND 2 (FOR BUILDING IN FIGURE 1-20).

porting floor level. These forces are equal to the product of the acceleration and the mass of the component. In the case of a rigidly mounted component that is itself rigid, the accelerations that the component must endure are simply those of its support. In all other cases where either the component and/or the support has some flexibility, the response of the component may be amplified. The greatest amplication of component response will occur when the fundamental period of vibration of the component is near one of the predominant periods of the input motion of its Dynamic Environment.

The greatest amplification of component response will occur when the component's fundamental period is near one of the predominant periods of the input motion of its Dynamic Environment.

A response spectrum is usually used to represent the potential amplification of the response of a component (which can be modeled as a SDOF system) when subjected to the input motions of its supporting floor. These spectra are constructed in the same manner as the ground motion response spectra: a series of SDOF systems representing components of different mass and stiffness is subjected to a time history of floor accelerations; the maximum response obtained for each SDOF system provides a point on the floor response spectrum.

Figure 1-23 shows a three-story building subjected to input ground motions that result in building response represented as time-histories of acceleration for each of the floors as shown. For each floor a response spectrum was developed as described above. The spectra become very high and peaked in the region of the fundamental period of the structure T_s; thus, a component designed to have a period of vibration T_s, will experience high amplification of the input motions of its Dynamic Environment. In addition, floor response spectra often exhibit secondary peaks at other predominant modes of vibration of the building, and these must also be considered in design. If the component being designed is flexible and has the period of vibration shown as T_{flex} in Figure 1-24, nearly equal to the period of the structure T_s, then the response of the component will be highly amplified and will be many times greater than the floor input motions of its Dynamic Environment. On the other hand, if the component is very stiff and has a very low period of vibration, shown as T_{stiff}, in the range of about 0.03 seconds or less, the response of the component will be very nearly equal to the maximum acceleration of the floor to which it is anchored. Thus in those cases where there is close correspondence between the frequencies of the input motions of the Dynamic Environment and individual components, the component will be subjected to higher magnitudes of accelerations, increasing the possibility of more severe damage.



A) EARTHQUAKE INPUT MOTION (HORIZONTAL DIRECTION) B) STRUCTURE & COMPONENT (C) C) RESPONSE OF STRUCTURE TO EARTHQUAKE D) RESPONSE SPECTRA AT FLOOR LEVELS

FIGURE 1-23. BUILDING SUBJECTED TO TIME HISTORIES OF ACCELERATION WITH CORRESPONDING FLOOR RESPONSE TIME HISTORIES AND FLOOR RESPONSE SPECTRA.

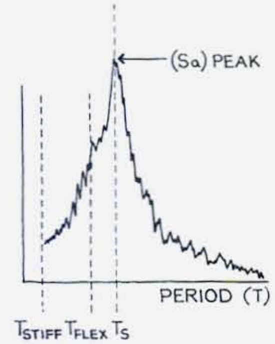


FIGURE 1-24. RESPONSE SPECTRUM FOR FLOOR 2 OF BUILDING IN FIGURE 1-23.

Example Nos. 2, 3, and 4 of Appendix A illustrate in more detail some aspects of building response, floor response, and component response. Example No. 2 compares the response of two buildings of similar height, one "stiff" and one "flexible." Example No. 3 discusses the differences in amplitudes of response with increase in story height. The results of analytical techniques are presented in this example and then compared to observations made of actual structures. Example No. 4 presents several historical floor response spectra from the 1971 San Fernando earthquake, and makes observations on the potential response of components when subjected to the given floor motions. From a practical design viewpoint, the information available from both analysis and historical records suggests the following conclusions regarding a component's response due to the input floor motions of its Dynamic Environment:

- It is entirely possible for a building component to have an acceleration response several times greater than the maximum acceleration of its supporting floor.
- Amplified component response may be caused by several modes of building response. Thus designs which assume that only significant amplifications are possible around the fundamental period of a building may be unconservative.
- The location of a component in a building can be an important factor in determing the periods of predominant floor motion.

CONCLUSION

This chapter has presented an overview of the nature of earthquakes and their effects on building and component response. The interactive nature of the earthquake phenomenon and its effect on building and component response can be summarized as follows:

- The energy released by an earthquake is transmitted and filtered through the earth reaching the site in the form of stress waves that have been altered by the geological formations through which they have traveled.
- At a given site, the motions that have traveled to it are further altered by the site's geophysical properties, resulting in ground motions whose characteristics are different from those of the motions that first emanated from the source of the earthquake.
- Ground surface motion, or "ground shaking," serves as the input motion to a building on a site. In cases of particularly complicated site conditions or building requirements, the building may also have an effect on the input ground motions.
- A building responds to input ground motion according

to its dynamic characteristics, which are, in turn, dependent upon the building's physical properties: mass, stiffness, and damping.

- The response of a building is not uniform throughout. The response -- the relative displacement and vibrational effects -- in any particular location in the building is called the Dynamic Environment. Each component or system of components must be designed for its particular Dynamic Environment.

Much is yet to be learned about the important factors governing building response and the resulting in-building motions. However, recent investigation has provided many useful observations and analytical techniques that can be applied successfully in the design process to produce buildings that respond favorably in earthquakes, and that meet economic, functional, and aesthetic requirements. The overview of earthquakes and building response presented in this chapter will serve as the basis for the development of a conceptual Dynamic Model in Chapter Two, which will incorporate the principles of seismic interaction into the context of architectural design.

Chapter Two

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The Dynamic Model of Building Component Interaction and the Design Process

Chapter One presented an overview of the basic concepts relating to earthquakes and building response which architects must understand in order to design components and systems to accommodate seismic motions. Earthquake-induced motions were described as they are transmitted along a path from their point of origin: waves travelling to a site are filtered and modified according to the earth's geotechnical properties along the way; the site's individual geotechnical characteristics alter the waves to produce a characteristic site response; ground shaking becomes the input motion to the building as a whole; and the building's response to that input motion determines the input motions for each building component according to its location in the building. Based upon consideration of these principles, architects should keep in mind that a building's motions are only approximated by equivalent static loads. The input motions to a building are dynamic and they are erratic in their frequency, their magnitudes, and their directions. Although static approximations can be used in some cases, they can also lead to an inadequate intuitive notion on the part of the architect as to what the nature of the building's motions will really be. Particularly in the case of flexible structures, components, and systems of components that deflect significantly, an architect must understand the potential motions of those parts under seismic loading.

Static approximations can lead to an inadequate intuitive notion of the real nature of a building's motions.

This chapter will describe why the concepts presented in Chapter One make it necessary for architects to design buildings for dynamic motions rather than static approximations of those motions. To this end a Dynamic Model is introduced which describes the building in its dynamic context, emphasizing the notion that the building and the ground beneath it are a sum of parts all interacting to greater and lesser degrees. All parts ultimately determine the response of the building as a whole and, in turn, the response of individual components and systems.
The significance of the Dynamic Model in the design process is then discussed: when and how it influences a designer's decisions. The Dynamic Model affects decisions about both overall building form and individual component design, and serves to alert the designer to seismic factors that may be important early in the design process but that are traditionally considered much later. Finally, in order to design components for seismic movement, one must be able to identify the source and type of motions, or "Dynamic Environment," to which each component is subjected. The concept of the Dynamic Environment will be defined in terms of vibrational and displacement effects so that designers may utilize their knowledge of seismic motions to formulate seismic criteria for the design of various systems and components.

THE DYNAMIC MODEL

Traditional Assumptions Regarding Architectural Design for Earthquakes

Designers have traditionally made two major assumptions that affect their approach to designing buildings for earthquakes. The first assumption is that buildings are an assembly of components or systems of components that perform operational roles: structural components serve structural roles, while enclosure, finish, and service components serve other operational functions. This view of buildings groups components as follows:

- Structural Systems: those components whose primary function is carrying loads -- columns, beams, floors, bearing walls, and horizontal and vertical shear diaphragms.
- Non-Structural Systems:
  Enclosure Systems: components such as infill walls, curtain walls, spandrel covers, precast panels, and so forth.
  Finish Systems: interior components such as partitions, ceilings, veneers, and so forth.
  Service Systems: components for heating, lighting, air conditioning, communications, and transportation.

Any building component may act structurally, be it part of the structural, the enclosure, the finish, or the service systems, and may alter building response.

The above operational grouping implies that components are either "structural" or "non-structural," which is a dangerous oversimplification when designing buildings for earthquakes. Actually, any one component may act structurally, be it part of the structural, the enclosure, the finish, or the service systems, and may alter the response of a building and its components to an earthquake. Traditionally "non-structural" components may in fact behave structurally and improve or impair the building's ability to endure an earthquake without damage.

The second assumption that architects have made is that of thinking of earthquake loads as being similar to wind or other lateral loads: for design purposes the building is considered in a state of equilibrium and static loads "equivalent" to dynamic forces are applied at each floor level of the structure parallel to the coordinate axes of the building. This simplification gives the architect the erroneous impression that the building is vibrating only in one axis and that the dynamic loads are applied as if they were static, when, in fact, the motions to which the building is subjected are not only erratic in their mag-

The motions to which a building is subjected are erratic in their magnitudes and frequencies, multidirectional, and induced at the base of the building.

nitudes and frequencies, but also multidirectional and induced at the base of the building. Individual components adjacent to them are considered to be static, another simplification that is misleading in terms of the components' relative displacements and vibrational response.

The degree to which any component contributes to the response of the building is dependent upon the degree to which that component interacts with all of the other component parts of the building. As a result, in order to asses more accurately the contributions of various building components during earthquakes, they will be organized into a model based upon their mutual interaction during dynamic response.

Engineering Basis for Building Design -- Coupled and Uncoupled Components

dynamically "coupled" components

dynamically "uncoupled" components

Each and every component in a building interacts with other components and contributes to the response of the building as a whole, but some components are more influential in determining the character of the response than others. The interaction between two components is dependent on the components' dynamic characteristics and can be said to be of two types, one more influential on the building's overall response, and one less so. In the first type of interaction, one component significantly influences the response of the other to which it is attached or with which it may come in contact during seismic activity, and vice versa; these components are said to be dynamically "coupled," and must be analyzed as one system and designed to be dynamically compatible with one another. In the second type of interaction, one component influences the response of a second component, but the second does not significantly influence the response of the first; the motion of the first component is used as the input motion for analyzing the second component's response. In this condition the two components are said to be dynamically "uncoupled"; these components must also be designed to be dynamically compatible.

A Dynamic Frame of Reference for the Architectural Design Process

For structural engineers the distinction between coupled and uncoupled components is enough to analyze a building and its components in a dynamic frame of reference. The building's structural system as well as all of the elements which may influence the building's response are treated as coupled systems. Those components that are not significantly interactive are uncoupled and do not have to be considered in the design of the structural system, except as permanent live loads. But for the architectural design of building components, the coupled-uncoupled distinction alone is not adequate. The architectural design process requires the identification of three types of components whose roles in the interaction process are different. The different component types are as follows:

The coupled-uncoupled distinction between building components is not adequate for architectural design.

- Those components that are conceived of as working together to provide the building's essential capacity to endure earthquake motions.
- Those components that are not conceived of as contributing to the building's capacity to endure earthquakes, but because of their physical properties will influence the building's response.
- Those components that are conceived of as having insignificant influence on the response of the building as a whole.

The above component types acknowledge the differences between the architect's conceptual design responsibilities and the more purely analytical responsibilities of the engineer.

Structural engineers normally design and detail only for those components that give the building the capability of enduring earthquakes of various intensities with specified levels of structural damage. Engineers consider the first two of the above groups to be coupled systems -- they influence the response of the building as a whole and therefore must be included in the basic structural analysis of the building. The third group of components needs to be designed only to withstand the motion imposed by the coupled elements: none of these components significantly affects the overall building response, and hence they are not considered in the basic structural analysis for the building as a whole.

For architects each of the three types of components has different design implications. Components that are expected to be relatively permanent, that are physically capable of being designed to improve response, and that are economically feasible, can logically be incorporated into the building to improve its response. Such components can be very beneficial in reducing the initial cost of the structural system and/or in improving building response during an earthquake, thus increasing life-safety and reducing damage. Hence, at the preliminary design stage architects should discuss with their engineers which components in addition to the traditional structural system would be likely candidates for incorporation into the lateral force resisting system of the building, either to improve its response in terms of accelerations or displacements, or to increase its strength to endure the forces due to accelerations.

Some components may not logically be incorporated into the structural system because they either:

- are not expected to be permanent for the lifetime of the building;
- would be too expensive to incorporate into the structural system;
- have physical properties (mass, stiffness, configuration, location in the building, strength, damping) that would have a detrimental effect on the response of the building;
- would cause problems in the functional layout or aesthetic concept of the building.

Because of their physical properties, however, certain components that should not be part of the structural system, cannot be considered uncoupled from it either. These components present a special challenge to the design team, for potential positive effects cannot be relied on; yet, their negative effects must be accounted for in the structural analysis and in the design of the component. Thus, architects must work closely with engineers when designing and detailing coupled systems that are not part of the structural system, but by their nature may affect the response of that system. Architects will want to design such components to minimize any potentially negative impacts they might have on the building's response and to eliminate their potential for damaging components of the structural system.

Some components, because of their inherent physical properties cannot be designed to improve the response of the building and have so little influence on building response, positively or negatively, that they can be neglected in the design of the structural system. Such components are uncoupled and are not included in the structural analysis of the building except for their dead weight.

Architects must design both the coupled components that are not part of the structural system and the uncoupled components to endure the dynamic motions imposed upon them. For each type of component the input motions are not those of the ground, but the motions of the particular section of the building in which the component is located. For example, if the component is a partition attached to the upper and lower floor slabs, then it will be subjected to the input motions of these two floors, which will differ from the ground input motion. This component will also be subjected to the potential changes in configuration caused by the tendency for the two floors to displace in different directions and/or by different amounts. In addition, the partition's motions must be compatible with the motions of any other adjacent systems, such as ceiling, mechanical equipment, and so forth. Although all components may directly interact and contribute to the overall building response, for component design, one need consider only the building response at the component's location, its "Dynamic Environment." Thus, the architect must design a component to be compatible with its Dynamic Environment, which will include the input motions of adjacent components and systems in terms of accelerations and frequencies, and the displacement patterns in terms of distances and directions. Two components or systems will be considered "compatible" if the motions of one do not cause damage to the other system, and vice versa. As will be discussed later in this chapter, the concept of the Dynamic Environ-

The architect must design a component to be compatible with its Dynamic Environment, which will include the input motions of adjacent components and systems.

compatible components

ment will serve as an important tool for both establishing design criteria and formulating design strategies for individual components.

A Dynamic Model for the Architectural Design Process

Based upon the dynamic interaction of the ground and the building, the nature of coupled and uncoupled components in the architectural context described above, and the concept of the Dynamic Environment, a dynamic model is now presented which describes four elements: the ground and three building elements of varying types of interaction. These elements provide sufficient definition of the dynamic roles of components during collective interaction so that architects can better understand the role of dynamics in the design process, both in working with engineers and in their own design tasks. The model is presented in two parts, the first being a description of the interactive role of building components in determining building response, and the second being a description of the interaction of building components in their Dynamic Environments. The four basic elements of the Dynamic Model are the Ground, the Dynamic Structure, Coupled Elements, and Uncoupled Elements, and are defined below.

The Dynamic Model: Component Interaction and Building Response

- The Ground (Gnd) is the region of soil materials adjacent to and beneath the building through which seismic waves are transmitted as input motion to the building (⇛). In some cases the input ground motions may be altered by the presence of the building (⇚⇛).
- The Dynamic Structure (DynS) is the combined form of the traditional structural system and those enclosure, finish, or service systems whose permanence, function, and physical properties make them suitable for improving the building's response. By definition all of the

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[1] Readers familiar with the Interaction of Building Components During Earthquakes study written by MBT under an earlier grant from NSF (1974) should note that the names of the elements of the Dynamic Model have been changed. The study team's use of the model since the publication of the first study suggested the revised names, which more accurately describe the various dynamic roles.

components in the Dynamic Structure must be dynamically coupled. The Dynamic Structure is responsible for the dynamic integrity of the building as a whole. Sometimes exterior cladding elements, stair towers, elevator shafts, heavy mechanical equipment and ducts, and so forth, can be successfully incorporated into the Dynamic Structure.

- Coupled Elements (CpEl) are those components of the enclosure, finish, or service systems that cannot be incorporated into the Dynamic Structure because they are unlikely to be permanent over the life of the building, they would be too expensive to incorporate, their physical properties would have a detrimental effect on building response, and/or they would cause problems in the functional layout of the building. Yet these elements have properties that will significantly affect the response of the Dynamic Structure and thus the building as a whole. These elements are coupled because the Dynamic Structure imposes the motions which they must endure and because they in turn influence the response of the Dynamic Structure. These elements must be considered in the analysis and design of the Dynamic Structure, and may contribute either positively or negatively to the building's dynamic integrity. They must also be designed to endure the input motions of their Dynamic Environments. Components that may potentially be Coupled Elements are heavy or rigid partitions and enclosure walls, major pieces of mechanical equipment, stair towers, elevator shafts, and so forth.
- Uncoupled Elements (UncEl) are those components of the enclosure, finish, or service systems that may not appropriately be considered an integral part of the Dynamic Structure, and have dynamic characteristics that do not significantly affect the building's response. Except for their weight, Uncoupled Elements can be neglected in the seismic design or analysis of the Dynamic Structure. They must always be designed to endure the input motions of their Dynamic Environments. Lightweight and relatively flexible components of the enclosure, finish, and service systems would normally be Uncoupled Elements.

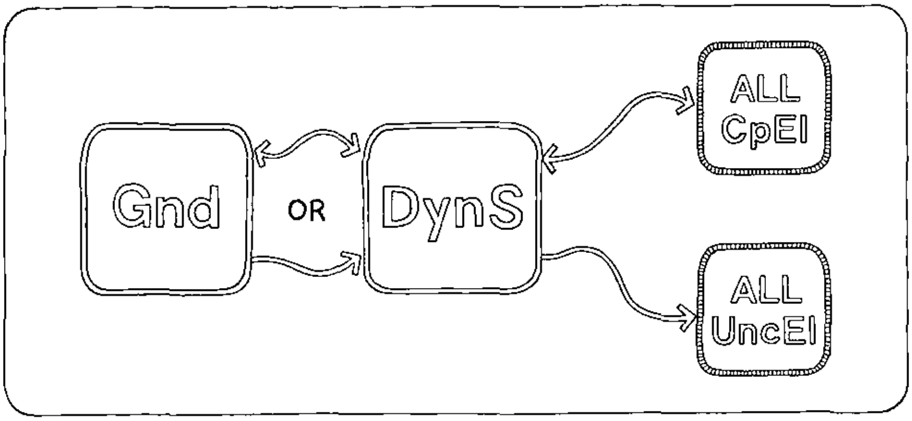


FIGURE 2-1. DYNAMIC MODEL OF BUILDING RESPONSE.

Figure 2-1 is a diagram of the Dynamic Model that summarizes the "dynamic roles" of components (Gnd, DynS, CpEl, UncEl) and the corresponding interaction between them. The Ground is shown as providing the input ground motion to the Dynamic Structure and the either/or arrow indicates that in some cases the phenomenon of site-building interaction must be taken into account. The double-headed arrow between the Dynamic Structure and Coupled Elements indicates that the Dynamic Structure influences the response of the Coupled Elements and the Coupled Elements influence the response of the Dynamic Structure. The single headed arrow between the Dynamic Structure and Uncoupled Elements indicates that the Dynamic Structure influences the response of the Uncoupled Elements, but Uncoupled Elements do not significantly influence the response of the Dynamic Structure. All of these Elements taken together form the building, and their collective interaction results in the building's response.

The Dynamic Model: Component Interaction and the Dynamic Environment

The building response portion of the Dynamic Model accounts for the influence of components on total building response and requires that all components be designed for their Dynamic Environments. Similar principles can be applied to the interaction between various Coupled and Uncoupled Elements. In addition to the motions imposed by the Dynamic Structure, a component must also undergo the input motions of other Coupled and Uncoupled Elements that are

To analyze and design various building systems, one must understand the nature and possible extent of interaction between different Elements, as well as their interaction with the DynS.

adjacent or anchored to the given component. In order to be able to analyze and design various building systems such as ceilings and partitions, one must thoroughly understand the nature and possible extent of interaction between different Coupled and Uncoupled Elements, as well as their interaction with the Dynamic Structure. Figure 2-2 summarizes the interactive relationships between components with different dynamic roles in terms of their Dynamic Environments. Coupled and Uncoupled Elements interact with other Elements of their Dynamic Environment in varying degrees from minimal to total. For design purposes, the possible influence of one component on another can be approximately described by two different types of interaction, shown in Figure 2-2:

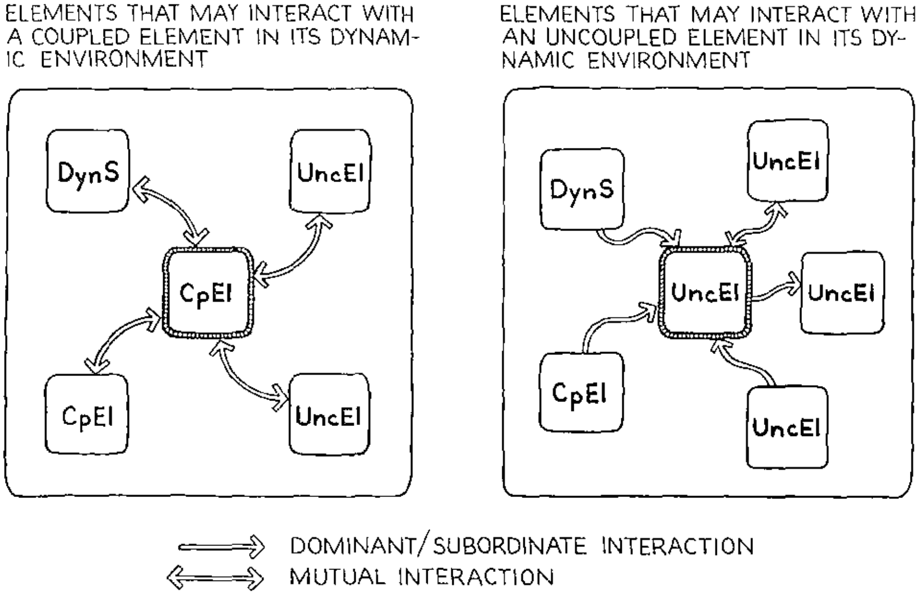


FIGURE 2-2. THE DYNAMIC ENVIRONMENT FOR COUPLED AND UNCOUPLED ELEMENTS.

dominant/subordinate interaction

- Dominant/Subordinate Interaction (⟹): One component may influence another component's response, but the second may influence the response of the first very little: the component that influences the response of the other component to a significant degree will be called the "dominant" component, and the component influenced under such circumstances will be called the "subordinate" component. For instance, if a lightweight lay-in tile ceiling is attached to a relatively stiff partition, the partition's motions will be likely to dominate the ceiling system's motions and significantly influence its response to an earthquake.

- Mutual Interaction (⇔): If one component's motions affect the other component's response and vice versa, then the two components are said to be mutually interactive. For instance, if two similar partitions are anchored to each other, they are likely to influence each other's response to approximately the same degree.

Analagous to the Dynamic Model, if one component influences another but is not influenced itself, then there exists a dominant/subordinate relationship, denoted by the single headed arrow pointing toward the dominated (subordinate) component. If one component influences the second and vice versa, then there is a state of mutual interaction denoted by a double headed arrow signifying the influence of each component on the other. Figure 2-3 is a group of examples demonstrating hypothetical instances of the different types of interaction between Coupled and Uncoupled Elements. For convenience of reference, Figure 2-4 summarizes the Dynamic Model and analagous dominant/subordinate and mutual interaction relationships.

THE DETERMINATION OF A COMPONENT'S DYNAMIC ROLE

The Dynamic Model describes the effect of the different possible dynamic roles of a component both on overall building response, and on the component's individual response to its Dynamic Environment. In order for the conceptual distinctions of the Dynamic Model to be useful in the design process, the manner in which a component's dynamic role is determined or designed must be described in more detail. The dynamic role of a component is determined by its physical properties and interface conditions, architectural programming and design decisions, and economics. The physical properties and interface conditions of the component determine whether a given component can be designed as part of the Dynamic Structure, a Coupled Element, or an Uncoupled Element. The other factors determine which dynamic role is desirable for a given component. All factors affect design decisions regarding the degree

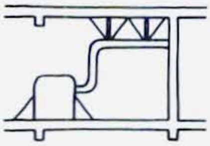
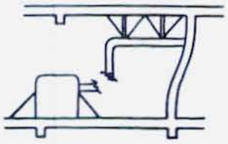
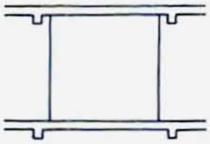
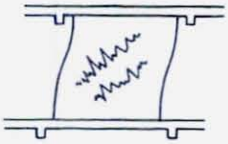
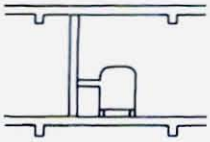
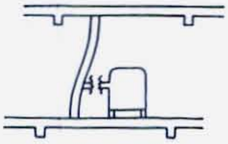
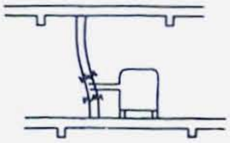
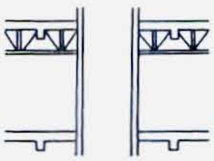
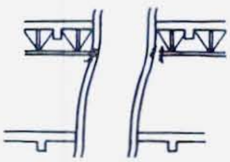
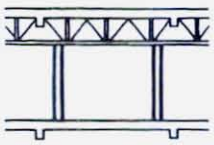
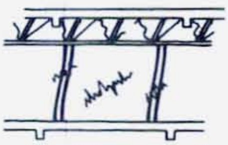
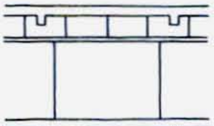
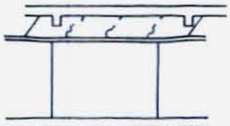
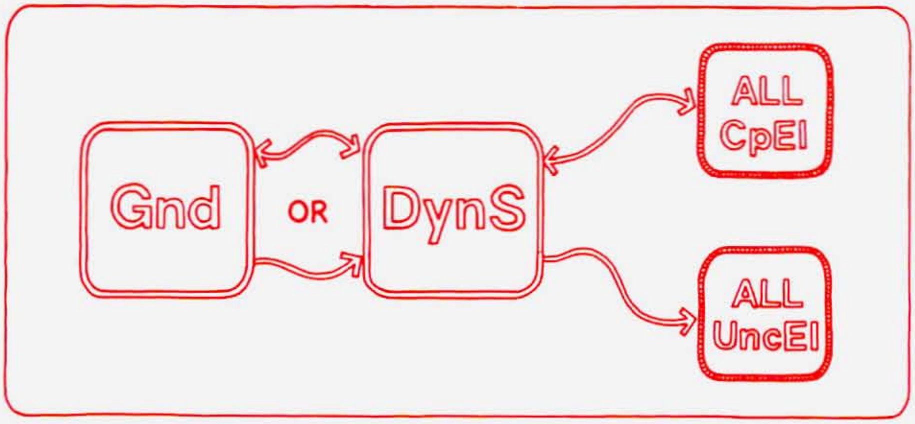
TYPE OF INTERACTION BETWEEN COMPONENTS	COMPONENTS AT REST	COMPONENT INTERACTION	COMMENTS
DynS ⟺ CpEl			Braced equipment (CpEl) influences response of DynS; DynS influences response of equipment. Either one could damage the other.
DynS ⟹ UncEl			DynS influences response of partition (UncEl); partition attempts to brace DynS and fails.
CpEl ⟺ CpEl			Mechanical equipment (CpEl) influences response of fire-rated wall (CpEl) and may damage it; fire-rated wall influences response of mechanical equipment and may damage it.
			
CpEl ⟹ UncEl			Elevator shaft (CpEl) influences response of ceiling (UncEl) and may damage it. Ceiling will not influence response of shaft.
UncEl ⟺ UncEl			Interior partitions (UncEl's) are connected to braced ceiling system (UncEl); each influences the other's response and mutual damage may result if there is significant interstory relative displacement and the connection between the two is strong.
UncEl ⟹ UncEl			Partitions (UncEl's) move with floor and are attached to ceiling system (UncEl). Ceiling system must deflect if there is interstory relative displacement.

FIGURE 2-3. EXAMPLES OF DOMINANT/SUBORDINATE (⟹) INTERACTION AND MUTUAL (⟺) INTERACTION BETWEEN COUPLED AND UNCOUPLED ELEMENTS.

DYNAMIC MODEL

GROUND (Gnd) is the region of soil materials adjacent to and beneath the building through which seismic waves are transmitted as input motions to the building ⇒. In some cases the input ground motions may be altered by the presence of the building ⇔.

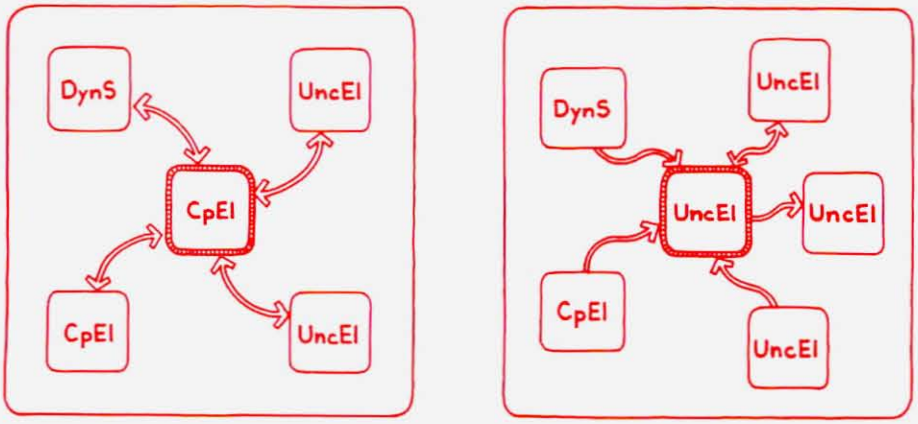
DYNAMIC STRUCTURE (DynS) is the combined form of the traditional structural system and those enclosure, finish, or service systems whose permanence, function, and physical properties make them suitable for improving the building's response.



COUPLED ELEMENTS (CpEl's) are those components of the enclosure, finish, or service systems that cannot be incorporated into the DynS for reasons of impermanence, function, or physical properties. Yet these components have properties that will significantly affect the response of the DynS and thus the building as a whole.

UNCOUPLED ELEMENTS (UncEl's) are components of the enclosure, finish, and service systems that may not appropriately be considered to be an integral part of the DynS, and have dynamic characteristics that do not significantly affect the building's response.

DYNAMIC ENVIRONMENTS
of CpEls and UncEls



DOMINANT/SUBORDINATE INTERACTION ⇒. One component may influence another component's response, but the second may influence the response of the first very little: the component that influences the response of the other component to a significant degree is dominant, and the other component is subordinate to it.

MUTUAL INTERACTION ⇔. If one component's motions affect another component's response and vice versa, then the two components are said to be mutually interactive.

FIGURE 2-4. THE DYNAMIC MODEL OF BUILDING RESPONSE AND THE DYNAMIC ENVIRONMENT FOR COUPLED AND UNCOUPLED ELEMENTS.

of interaction of components with the Dynamic Structure; however, physical properties alone govern the distinction between Coupled and Uncoupled Elements. Each factor is described below in terms of its effect on both overall building design and individual component design.

PHYSICAL PROPERTIES AND INTERFACE CONDITIONS

Mass

Relatively heavy components are more likely to be either part of the DynS or CpEl's; lightweight components are more likely to be UncEl's.

The mass of each and every building component is considered in the design of a building's structural system. The total mass of the building can significantly affect its period of vibration and, hence, its response to input ground motions. The mass of a component relative to the mass of the Dynamic Structure will be a major factor in determining the dynamic role of that component. Relatively heavy components are more likely to be either part of the Dynamic Structure or Coupled Elements, while relatively lightweight components are more likely to be Uncoupled Elements. The mass of a Coupled or Uncoupled Element will also affect the degree of interaction it will have with other Coupled or Uncoupled Elements. If the mass of the two components differs significantly, there will probably be a dominant/subordinate relationship. If the masses are similar, there will be greater potential for mutual interaction.

Stiffness: Material Stiffness, Configuration, Interface Conditions

"Stiffness" is a comprehensive term that includes material stiffness, configuration in plan and section, and interface conditions (type of, or lack of connection at the interface between two components). No accepted terms exist that precisely describe the effect of stiffness on overall building response. An approximate distinction is made between buildings that are "flexible" and those that are "stiff"; this distinction is best used relatively to indicate that one building is more flexible or more stiff than another one.

"Stiffness" includes material stiffness, configuration, and interface conditions.

Stiffness applied to individual components includes material stiffness, configuration, and the type of connection at the interface between the component and another component, which allows the stiffness characteristics of the component to be transmitted or not transmitted to other components.

Material Stiffness

"Material stiffness" is the elastic resistance of a material to deformation (a material that is three times as stiff as another material will elongate one third as much when subjected to the same loads). The material stiffness of every building component contributes to the building's overall stiffness and, thus, to its ability to endure earthquakes. Building components whose materials are stiff may be incorporated into the Dynamic Structure of relatively stiff buildings. In a relatively flexible building, such components are likely to be incompatible unless their interface conditions allow for the differences in relative stiffness. Differences in the material stiffness of two Coupled or Uncoupled Elements in a Dynamic Environment partially determine whether they are dominant/subordinate or mutually interactive.

One of the major causes of earthquake damage to building components is the design of those components by architects who do not fully understand the consequences of joining together components of different stiffnesses. The anchorage of components to each other is often essential to their stability; but if two components have different relative stiffnesses, then stresses may be induced that are greater than those created by the component's own vibration. For instance, three components may be equally strong in terms of their ability to withstand the stresses caused by their own vibrations. However, if these three objects are interconnected or tightly abutt each other, then they are no longer free to deflect according to their own dynamic characteristics. Instead, the stiffest component will attempt to support the more flexible components connected to it, and may fail in its effort to do so. Thus, relatively stiff components attempt to restrain relatively flexible components regardless of their individual strengths.

Configuration

"Configuration" describes several geometric qualities of a *"configuration" includes height, geometry of plan and section, and location of dynamic-motion-enduring components.*

building including its height, geometry and continuity of plan and section, and location of dynamic-motion-enduring components (either part of the Dynamic Structure or Coupled Elements). Lack of symmetry with respect to any of these factors will produce differences in stiffness between different parts of the building. As a result, the building may rotate about its vertical and/or horizontal axis, producing displacement patterns that vary from area to area or floor to floor.

Configuration affects a component's stiffness and, hence, its ability to deflect or displace in various directions relative to other components. This ability will, in turn, partially determine the type of the component's interaction (either dominant/subordinate or mutual).

Interface Conditions

When two systems are connected or come in contact with one another, motions will be transmitted between them. The number of components in a building whose interface conditions are such that they transmit motions to other components has a significant influence on total building response. Rigid connections and tight interface conditions between many components may stiffen a building and modify its response; lack of such connections may result in a relatively flexible building response. When a component is stiff and suitable for sustaining earthquake motions, its connections must also insure that such motions will be transmitted to it in the directions in which it is capable of enduring them. When stiff components would stiffen a building's response in an undesirable manner, the connection at the interface with the Dynamic Structure may be designed to minimize the negative impact of the component on the building's response. The type of interface between two components will determine in what directions motions will be transmitted, and may alter one component's ability to be dominant, subordinate, or mutually interactive with another component.

The type of interface between two components will determine in what direction motions will be transmitted.

Strength

Designing components to be stronger may not improve the response of a building to input motions; the accelerations

A component may be quite strong and still fail at low level earthquakes because of its mass, stiffness or damping.

and displacements of the building are determined by its mass, stiffness, and damping, but not by its strength, except when a component's physical properties have been altered by failure. Neither will strength alone influence whether a component is part of the Dynamic Structure, a Coupled Element, or an Uncoupled Element. However, strength may determine the force level up to which a component may function in the dynamic role that the mass, stiffness, and damping have otherwise determined for it. As far as the design of individual components is concerned, a component may be quite strong and still fail at low level earthquakes because of its properties of mass, stiffness, or damping. The component may be strong enough not to fail under stresses imposed by accelerations, and still be so flexible that it will displace greatly and damage adjacent components. In such a case, the component is likely to be a Coupled Element. Relatively weak components are likely to be designed as Uncoupled Elements, since their strength will not allow them to continue functioning as part of the Dynamic Structure or as a Coupled Element at moderate and higher level earthquakes (see also the next section on the change of dynamic roles according to the severity of the earthquake).

Damping

The current level of sophistication in analytical methods is such that little control can be exercised over the amount of damping, or energy dissipation, in a building. Engineers design components using damping coefficients that vary between about one-half and ten percent, depending on the configuration and materials of the component under consideration. Altering or increasing the way in which the Gnd-DynS-CpEl-UncEl system dissipates energy is a potential method of attenuating response and thus decreasing the overall amount of damage to the Dynamic Structure, Coupled Elements, and Uncoupled Elements. The various proposals incorporating this method are described by two general categories: "add-on energy-absorbing devices" and "material damping" schemes. Both types of proposals have major problems that must be overcome before they can be used economically to improve building response.

For component design, engineers take damping into account by using damping coefficients between about one-half and ten percent; small coefficients typically apply to smaller building components; larger coefficients, two, five, and ten percent, apply to components of the Dynamic Structure. Ten percent damping is typically used for severe earthquakes, during which the building is expected to experience structural damage, but not collapse. Components that may contribute to the damping of the overall building response are particularly beneficial if their other physical properties and interface conditions allow them to be part of the Dynamic Structure. Those components that do little to damp the structure's response may still be designed to be part of the Dynamic Structure or to be Coupled Elements.

ARCHITECTURAL PROGRAMMING AND DESIGN CONSIDERATIONS

A component may have physical properties that permit it to be part of the Dynamic Structure, but, because of architectural programming or design considerations, such incorporation may not be desirable. Decisions to design a component to be a Coupled Element or an Uncoupled Element are similarly affected. The various programming and design considerations that affect a component's dynamic role are described below.

Relative Permanence of a Component

Relatively permanent components of a building are the most logical choices for incorporation into the Dynamic Structure. For example, heavy or stiff partitions in main circulation corridors (fire-rated walls) or stairwells, may be permanent over the life of the building and, hence, may be easily designed to be dynamic resistive elements in the Dynamic Structure. When adaptability to future change in spatial requirements is necessary, designers must be careful not to incorporate components into the Dynamic Structure that will have to be removed or relocated in a few years' time. If a component has physical properties that would allow it to be designed as part of the Dynamic Structure, but the designer cannot rely upon its permanence, then it will most likely be designed as a Coupled Element: the component's positive or negative effect on building

When adaptability to future change in spatial requirements is necessary, components that will have to be removed or relocated in a few years' time must not be incorporated into the DynS.

response will be considered in the structural analysis of the building. The materials of the wall might also be changed to alter the physical properties of the wall significantly enough to allow it to be designed as an Uncoupled Element. When adding, removing, or relocating components in an existing building, the designer must remember that such alterations may change the response of adjacent components.

Functional Relationships of Activities and Services

If a component's physical properties make it a good choice for incorporation into the Dynamic Structure, its design for such a role must not interfere with the functional layout of the building. If the design of a component to be part of the Dynamic Structure results in interference with other programmatic and design requirements, such as column-free spaces, efficient circulation, location of mechanical and electrical equipment, and so forth, then the component may be more wisely designed to be either a Coupled or an Uncoupled Element.

Aesthetics

Sometimes the attempt to design a component for a particular dynamic role will result in a design that is aesthetically unacceptable or undesirable. For example, if incorporation of exterior enclosure wall panels into the Dynamic Structure results in an undesirable aesthetic treatment of the building's facade, then the architect may wish to design the exterior wall as a Coupled or an Uncoupled Element instead. Architects must consider aesthetic implications of dynamic roles at the same time that they consider costs, function, life-safety, and the component's physical ability to be designed for different roles.

Climatic, Acoustic, and Fire Isolation Requirements

When components are likely to be designed as Uncoupled Elements, problems may occur if the designer also attempts to satisfy fire, acoustic, or climatic requirements. For instance, the design of a partition to be an Uncoupled Element may result in connections that do not prevent noise from being transmitted to adjacent spaces. If the partition were designed as a Coupled Element or as part of the Dynamic Structure, such isolation might be more easily achieved. In some cases both the uncoupled role and acoustic isolation may be easily designed for; in other instances, the designer may have to expend more time and effort to design an Uncoupled Element for fire, acoustic, or climatic isolation.

ECONOMICS

Designing a component to be part of the DynS may increase its cost, but it may also improve building response and reduce long-term costs of repair and replacement.

The economy of designing systems to be part of the Dynamic Structure, Coupled Elements, or Uncoupled Elements is as much a part of the dynamic role decision process as either physical properties or programming and design decisions. Cost is always a factor in design decisions, and the relative economic value of alternative design solutions must be evaluated, with initial costs balanced against level of risk and the potential cost of repairing damage. The decision regarding cost is in large part subjective, because precise estimates of such trade-offs are very difficult to achieve. Designing a component to become part of the Dynamic Structure may increase its cost, but it may also improve the building's response and hence reduce the long-term costs of repair and replacement. Improving the response of Coupled Elements is sometimes quite costly; improving the response of Uncoupled Elements is sometimes quite inexpensive. For either type of element the resulting reduction in long-term costs of repair and replacement may be difficult to predict.

SUMMARY OF THE FACTORS INFLUENCING A COMPONENT'S DYNAMIC ROLE

The dynamic role of a component is based upon its physical properties and interface conditions, architectural programming and design considerations, and economics. These factors are summarized in Figure 2-5, which also elaborates the requirements and conditions associated with the different dynamic roles:

- The categorical distinction used by engineers for the design of the component, either coupled or uncoupled (see earlier discussion in this chapter).

	DYNAMIC STRUCTURE (DynS)
PHYSICAL PROPERTIES AND INTERFACE CONDITIONS:	
MASS	- Similar to that of the structural frame
STIFFNESS	- Similar to that of the structural frame
CONFIGURATION	- Can be easily incorporated into the structural frame
STRENGTH	- Similar to that of the structural frame
CONNECTION AT INTERFACE	- Connections permit component to respond with the structural frame
ARCHITECTURAL PROGRAMMING AND DESIGN CONSIDERATIONS	- Not removable - Not relocatable - Aesthetically acceptable - No climatic, fire, or acoustic problems
ECONOMICS	Economically feasible to incorporate component into the Dynamic Structure
LIKELY STATUS FOR ENGINEERING DESIGN OF COMPONENT	Coupled
MOTIONS TO BE ENDURED	Input ground motion
NORMALLY DESIGNED BY:	Structural engineer with participation of Architect
POSSIBLE DYNAMIC ROLE CHANGES	Will act as the Dynamic Structure until yield at forces associated with very severe earthquakes

FIGURE 2-5. FACTORS AFFECTING THE DYNAMIC ROLE OF A BUILDING COMPONENT

COUPLED ELEMENT (CpEl)	UNCOUPLED ELEMENT (UncEl)
- May be relatively heavy	- Relatively lightweight
- May be relatively stiff	- Relatively flexible
- May be dissimilar to DynS	- Configuration insignificant
- May be relatively strong	- Relatively weak
- Connections should control or reduce influence on response of the Dynamic Structure	- Connections prevent component from influencing response of DynS
- May be removable - May be relocatable - Aesthetically undesirable if designed as DynS - Cannot be designed as DynS for fire, acoustic, or climatic reasons	- May be removable - May be relocatable - Aesthetically undesirable if designed as DynS - Cannot be designed as DynS for fire, acoustic, or climatic reasons
May be economically unfeasible to incorporate into the Dynamic Structure or to design as an Uncoupled Element	Economically unfeasible to incorporate into the Dynamic Structure; economically feasible to control interaction with other components
Coupled	Uncoupled
Dynamic Environment for component's location: influence of DynS, other CpEl's	Dynamic Environment for component's location: influence of DynS, other CpEl's and UncEl's
Structural Engineer/Architect collaboration	Architect with some assistance from Structural Engineer
May act as part of the DynS during low to moderate earthquakes or during first seconds of larger ones. May improve or worsen building response. As damage increases, role may change to UncEl.	May act as part of the DynS at very low level earthquakes. Will not influence building response during moderate to high level earthquakes.

FIGURE 2-5 CONT'D.

- A description of design criteria: the source of accelerations and displacements for which a component must be designed.
- Participation of architects and/or engineers in the design of the component.
- Possible changes in the dynamic role of the component, depending upon the severity of the input motion to which it is subjected. The notion of changing dynamic roles depending upon the severity of the earthquake or its duration is an important one, and is discussed in the following section.

Changes in a Component's Dynamic Role According to the Severity of Input Motions

A component's dynamic role in a mild earthquake may be different from what it is in a moderate or severe earthquake; or, over the duration of the same earthquake, the dynamic role may change

A component's response will be dependent not only on its physical characteristics and interface conditions, but also on the magnitude of accelerations and displacements to which it is subjected. Because of this dependence, the dynamic role that a component performs may change according to the severity of input motions. Thus, in a mild earthquake, a component's dynamic role may be different from what it is in a moderate or severe earthquake; or, as a component is subjected to repeated motions over the duration of the same earthquake, its role may change.

In a mild earthquake, almost all components of the building may help stiffen it and affect its response. Under such conditions, even weak or fragile materials like glass may act as part of the Dynamic Structure. During a moderate earthquake, the relatively stiff, but weak and fragil components may attempt to act as part of the Dynamic Structure and stiffen the building, but they will not be strong enough to do so and will fail. Thus, architects must take into consideration both building response and individual component response when designing a component for its dynamic role(s) at different levels of seismic motions.

The dynamic roles that various components may assume during earthquakes of different levels are described below, beginning with the most severe earthquake.

- For the earthquake judged to be the maximum possible at a given site, the design team may establish criteria that would insure that the building would not collapse, even though the Dynamic Structure would suffer damage. During the first second or two of the earthquake, when the motions are slight, Coupled Elements may act as part of the Dynamic Structure. However, the motions would rapidly become too great for the components, and they would eventually suffer extensive damage, acting as either Coupled or Uncoupled Elements. Ideally, the strategy for the design of the Coupled Elements is to limit the amount of damage they may cause to the Dynamic Structure when they fail.

- For the maximum probable earthquake, the design team may establish criteria requiring limited or no damage to the Dynamic Structure, and varying amounts of damage for Coupled and Uncoupled Elements. Those components having a high life-safety value or perhaps unusually high replacement value might be designed to withstand this earthquake with little or no damage. The cost of designing less critical components to withstand the Dynamic Environment imposed by such a severe earthquake is likely to be prohibitive; the hazards of such damage are slight and the cost of repairing or replacing the components relatively small. During the first few seconds of the earthquake, Coupled Elements may act as part of the Dynamic Structure. As the seismic motions became more severe, these components would be damaged and would probably act as Uncoupled Elements. Components designed to be Uncoupled Elements will act as such, regardless of the severity of motions or duration of the earthquake and the amount of damage they suffer.

- In a moderate earthquake, all components of the Dynamic Structure should remain undamaged, and some minor damage may occur to Uncoupled Elements. At this level earthquake, only those components designed to act as part of the Dynamic Structure will, in fact, do so. Components whose physical properties are such that they cannot help sustain the motions of the building as a whole should be designed so that they do not attempt to act as part of the Dynamic Structure during the severe motions of the earthquake, or they will fail. During the initial seconds of the earthquake, components designed as Coupled

Elements may, in fact, act as part of the Dynamic Structure. However, as the motions increase, they will assume their roles as Coupled Elements. In some cases Coupled Elements may even be damaged, and designers should be aware of this possibility and try to detail Coupled Elements so that they do not, in turn, cause inadvertent damage to the Dynamic Structure.

- For mild earthquakes, no components should be damaged and many components will significantly affect the response of the building as a whole. Coupled Elements are not deliberately designed to be part of the Dynamic Structure at a low level earthquake, but they will act as if they are. Components designed to be Uncoupled Elements will act as Uncoupled Elements even during mild earthquakes. Thus, in designing components to be Uncoupled Elements one loses their potential contribution to the stiffness of the building in return for insuring that they respond without damage during moderate earthquakes.

phased damage

design earthquakes

Ideally, knowing that a component's role may sometimes change according to the severity of input motions, one may be able to design the component so that during mild input motions it is not damaged, but at higher levels of motion it will fail in a controlled manner. The component would be designed to reduce its interaction with adjacent components, to permit economic repair, to insure that a more critical component will not inadvertently be damaged, and to prevent hazards to life-safety. This approach is called "phased damage." Because our present knowledge of damage thresholds is limited, such a precise method is not yet possible. Regardless of the design strategy, designers must be aware of the potential changes in the dynamic role of a component. Currently, components may be designed for dynamic roles in which they remain undamaged up to a certain level of input motions, or "design earthquake."

THE DESIGN PROCESS

The Dynamic Model describes the collective interaction that occurs between components during an earthquake. The use of this conceptual model in the building design process should enable architects to assess more accurately the effects of their design decisions on the response of a building and its components to seismic input motions. The Dynamic Model is a guide for deciding upon the most appropriate dynamic role for various building components. Then, the Dynamic Environment must be determined for each component so that specific design criteria can be formulated. The incorporation of these two concepts into the design process is summarized below:

- During the programming stage, the design team and the client must set criteria for the life-safety of the occupants of the building, and the level of damage that will be acceptable in terms of continued operation of the building and the costs of repair and replacement.
- A design peak ground acceleration, and a design ground response spectrum or suitable earthquake time history are developed for a particular site, based upon the site's physical properties, its location relative to faults, and the probability of activity along those faults.
- Alternative conceptual building designs are developed, and the Dynamic Model is used to define the most appropriate dynamic roles (Dynamic Structure, Coupled Element, Uncoupled Element) for the various components of the building.
- Structural engineers project the approximate period of vibration of the alternative building concepts; the various concepts can be checked for potential amplifications of response due to correspondence of the predominant frequencies of the ground and the building.
- Acceptable alternative design concepts are developed more fully, and specific building response calculated; the final overall building concept is chosen based upon programmatic objectives.
- The dynamic interaction of all components in the building will result in the building's overall response, which, in turn, will result in different dynamic conditions in different locations of the building. The resulting accelerations and relative displacements, the Dynamic Environment, combined with the programmatic requirements for the component, may be used to determine the design criteria for the component.

FIGURE 2-6. OUTLINE OF THE DESIGN PROCESS EMPHASIZING SEISMIC CONSIDERATIONS

PART I. BUILDING DESIGN

TASK	CONSIDERATIONS	PRODUCT
STEP A. PROGRAMMING: Formulate objectives:		
1. Functional needs	- Desired activities and their space requirements - Mechanical, electrical, plumbing services - Circulation systems - Adaptability to future change	Building performance standards: - Functional program - Human factors program - Seismic-safety program - Fire-safety program - Budget
2. Time and cost needs	- First cost - Maintenance costs - Time schedules	
3. Human factors	- Environmental psychology - Aesthetics	
4. Emergency needs: earthquake, fire, etc.	- Life-safety - Applicable codes - Continued operational use - Costs of repair due to damage from hazard	
STEP B. SITE ANALYSIS		
1. Select location on site	- Building performance standards - Soil and geological characteristics of site - Dependability of utilities, access routes	- Suitable site for development - Locational criteria for site planning

2. Determine seismic design criteria	- Seismological history of region
	- Soils and geological characteristics of region and of site (proximity to faults, etc.)
	- Considerations listed under earthquake emergency needs (see STEP A, 4.)
		- Seismic design criteria:
		  - design peak ground acceleration
		  - design ground response spectrum or earthquake time history

STEP C. GENERATE BUILDING DESIGN ALTERNATIVES by simultaneously performing tasks 1-3:		
1. Develop conceptual design alternatives	- Building performance standards - Seismic design criteria	- Relationships of spatial needs and circulation, mechanical, electrical, and plumbing systems - Basic systems and materials for DynS and suggested materials for finish components and service systems
2. Assign probable dynamic roles to components of each design concept	- Physical compatibility characteristics of building systems and materials: mass, stiffness, configuration, connectivity	- Designation of components as DynS, CpEl, or UncEl
3. Estimate approximate building response for each building concept	- Seismic design criteria - Overall building relationships, systems, materials - Component dynamic roles (DynS, CpEl, or UncEl)	- Probable general building response to seismic loads (flexible or stiff)
4. Identify schemes that are unacceptable under any circumstances	- Building performance standards - Building relationships, systems, materials - Approximate building response	- Alternatives designated as "viable" or "unacceptable"
STEP D. EVOLUTION OF DESIGN CONCEPT For viable alternatives, cycle through the following steps:		
1. Develop more specific schemes for conceptual design alternatives	- Building performance standards - Seismic design criteria - General building response	- General building design criteria: plan dimensions and story heights; materials, weight, etc. of components
2. Project more specific pattern of building response to seismic loads	- Seismic design criteria - General building design criteria	- Specific pattern of building response: relative displacement and vibrational effects
3. Evaluate alternative design concepts	- Building performance standards - Seismic design criteria - Building design criteria - Specific pattern of building response	- Selection of final design concept OR - Determination to proceed through design development again, modifying concepts to improve their viability

PART II. COMPONENT DESIGN

TASK	CONSIDERATIONS	PRODUCT
STEP A. FORMULATE DESIGN STRATEGY		
1. Formulate objectives for component		- Component performance standards
a. Functional needs	- Functional space and circulation relationships - Location in building configuration - Interface with other building components - Adaptability to future change	
b. Time and cost needs	- First cost - Maintenance costs - Time schedules	
c. Social needs	- Aesthetics - Environmental psychology	
d. Emergency needs	- Life-safety - Applicable codes - Continued operational use - Costs of repair due to damage from hazard	
STEP B. ANALYSIS OF THE DYNAMIC ENVIRONMENT		
1. Determine Dynamic Environment with aid of structural engineer	- General building response - Potential interaction of component with other components - Location in structure	- Dynamic Environment: relative displacement and vibrational effects
2. Determine design criteria for component	- Dynamic Environment - Component performance standards - Selected design approach	- Dynamic Environment design criteria
STEP C. GENERATE COMPONENT DESIGN ALTERNATIVES		
1. Develop conceptual design alternatives	- Dynamic Environment design criteria - Component performance standards	- Component material system and configuration
2. Assign dynamic roles to components	- Physical properties: mass, stiffness, strength, configuration, interface conditions - Design approach	- Designation of each alternative component design as CpEl or UncEl
3. Determine response of each component alternative	- Dynamic Environment design criteria - Dynamic role of component	- General component response and interaction with other components
4. Identify solutions that are unacceptable under any circumstances	- Component performance standards - General component response and its effect on adjacent components	- Component design concepts designated as "viable" or "unacceptable"
STEP D. EVOLUTION OF COMPONENT DESIGN CONCEPT		
1. Develop more specific design of component	- Component performance standards - Dynamic Environment design criteria - General component response and interaction with other components	- Specific component design criteria: size, material, weight, structural support system, aesthetics, and so forth
2. Project specific pattern of component response to seismic loads	- Dynamic Environment design criteria - Specific component design criteria	- Specific pattern of component response
3. Evaluate alternative design concepts	- Component performance standards - Interaction with other components - Dynamic Environment design criteria - Specific pattern of component response	- Select component design or cycle through STEP D, 1-3 again
STEP E. FINAL DETAILING OF COMPONENT		
1. Develop details of selected component concept	- Concept chosen - Compatibility with adjacent components	- Modified design detailed in working drawings, specifications
2. Preparation and review of shop drawings	- Modified design - Contractor's capabilities - Costs	- Shop drawings of design approved by architect
STEP F. CONFIRM THAT FABRICATION AND CONSTRUCTION MEET DESIGN CRITERIA		

- Individual building components may be designed and detailed for vibrational effects and relative displacement effects. These components must be connected such that 1) they can endure the shear, bending, and axial forces to which they will be subjected, and remain stable; and 2) they are able to accommodate the relative displacements of adjacent systems caused by interstory relative displacements and vibrational effects.

The outline should assist one in determining where in the design process the concepts of the Dynamic Model and the Dynamic Environment may improve the design of buildings.

Figure 2-6 outlines the design process while emphasizing seismic requirements. This outline should assist one in determining where in the design process consideration of the principles of the Dynamic Model and use of the Dynamic Environment may improve the design of a building and its components for seismic input motions. Although seismic considerations are described in detail for the purpose of emphasizing the importance of the principles in this study, design decisions are based upon the collective consideration of all building design criteria. These criteria include functional needs, time and cost requirements, human factors, and emergency requirements. Throughout the outline the term "building performance standards" is used to refer to the many and varied requirements considered in the design process that are not of a seismic nature.

The format of the design process outline simulates the means by which a design team approaches the design of a building. The major steps of the design process are shown in boldface and are accompanied by sub-headings that describe the tasks involved in each of the major design phases. On the left side of the outline is listed the task to be performed, in the middle, the major items that might be considered in performing the given task, and on the right, the end product of performing the task after accounting for all of the necessary considerations. Each "Product" is important not only in itself, but also as it affects subsequent design decisions. The "Products" arrived at in one design phase are design solutions that then become "Considerations" for other tasks later on in the design process. Thus "building performance standards" formulated in Part I, Step A, become "Considerations" in each of the major steps of Parts I and II. "Seismic design criteria" developed in Part I, Step B, become "Considerations" in steps C and D when building design alternatives are developed and evaluated. Similar relationships occur throughout the outline for the various "Products."

In any description of the design process there is the problem of defining the "typical" sequence of events. Approaches to design problems vary from project to project and team to team. An attempt is made in the outline to simulate some of the cyclical processes that occur during the design of a building. These simulations have been kept simple because it is impossible to forecast exactly when and how design decisions are made and changed.

Finally, the outline is divided into two major sections: Part I - Building Design, and Part II - Component Design. Part II must be utilized again and again in designing individual components and systems of components. Incorporated in the outline are considerations for interaction of the component being designed with other components that have been or will be designed. Thus, redesign will occur as a result of the influence of one component's design on the design of another.

COMPONENT DESIGN: THE DYNAMIC ENVIRONMENT

In order to utilize the concept of the Dynamic Environment in the design of a component, one must be able to determine both qualitatively and quantitatively the motions to which any particular component will be subjected. The Dynamic Environment consists of relative displacements and forces due to vibration, and design criteria for these effects can be determined by the architect with the assistance of the structural engineer. The following sections will present methods that can be used to ascertain the proper design criteria.

DESIGNING BUILDING COMPONENTS FOR RELATIVE DISPLACEMENTS

During an earthquake, a building will be subjected to many displacements, some of which will affect the Dynamic Environment of various building components. This section will define the various types of displacements that may occur, as well as demonstrate the conditions under which such displacements may be of critical importance.

Displacements can be described in terms of the Dynamic Model and are of two basic types:

- Ground displacements occur when ground motion causes the Dynamic Structure and any component anchored to it to displace an equal amount in the same direction.
- Relative displacements occur between any two points in a building due to its response to input ground motions, specifically:
  - between two components of the Dynamic Structure;
  - between a component of the Dynamic Structure and a Coupled Element or an Uncoupled Element;
  - between any two Coupled or Uncoupled Elements.

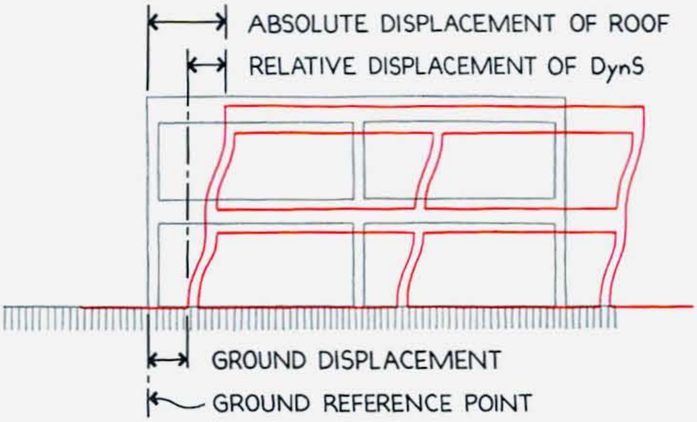


FIGURE 2-7. GROUND DISPLACEMENT, BUILDING RELATIVE DISPLACEMENT (DRIFT), AND ABSOLUTE DISPLACEMENT.

ground reference point

ground displacement

relative displacement

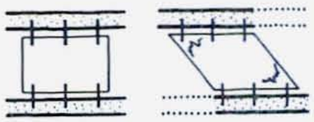
drift

absolute displacement

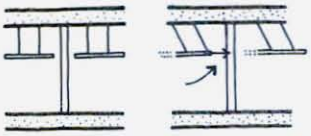
Due to earthquake ground motions, the Dynamic Structure displaces a distance relative to its "ground reference point," or original position, and this distance is known as the "ground displacement" (Figure 2-7). In addition to the ground displacement, the Dynamic Structure may displace an additional distance due to its own vibratory motion, which is known as its "relative displacement" (Figure 2-7), or "drift." Such displacement is usually significant only for buildings that are relatively flexible. When both the ground displacement and the Dynamic Structure's relative displacement are taken into account, the total displacement of any particular point of the Dynamic Structure is determined and is known as the "absolute displacement" (Figure 2-7). The same principle applies to any Coupled Element or Uncoupled Element anchored to the Dynamic Structure.

Acceleration of the Dynamic Structure or any component within it is partially related to the distance travelled by the component, its absolute displacement. But absolute displacement is not generally very useful in describing the response of the Dynamic Structure; rather, stresses and strains are determined by the displacement of the Dynamic Structure relative to its base. Similarly, for components anchored to the Dynamic Structure, only their displacements relative to other components are part of their Dynamic Environments.

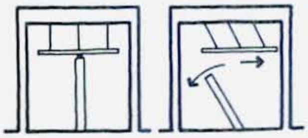
Relative displacements caused by the displacement of one point in a building relative to another point in a building may result in any of the following kinds of damage:



- Overstress: As a building component vibrates due to earthquake motions, displacement of the component may occur relative to its point of anchorage, causing stresses throughout the component. The vibratory motion produces flexural, shear, and axial stresses in the component, any of which may cause damage if they exceed the component's allowable stresses.



- Impact of Adjacent Components: If two components are displacing in opposite directions -- they are "out-of-phase" -- and they move towards each other, then damage may result from the knocking or hammering of the two components.



- Instability: If a component is excessively displaced, the support the component provides for another may be lost, creating an unstable condition.

The two basic causes of relative displacements in buildings are:

interstory relative displacement

1) Interstory Relative Displacements. The vibratory motions of the Dynamic Structure (induced by ground motion) cause individual components of the Dynamic Structure to deflect, thereby creating relative displacements between various points in the Dynamic Structure (Figure 2-8). Structural engineers calculate interstory relative displacements in their analysis of the building.

Some vertical displacement (much smaller than the horizontal) will occur due to interstory relative displacement.

component vibration

2) Component Vibration. Relative displacements are sometimes caused by components vibrating out-of-phase. Such out-of-phase vibration is caused by differences in the component's physical properties, including mass, stiffness, configuration, and damping. If deflections due to such vibration are not allowed for in the design of the interface between the two components, damage will result (Figure 2-9).

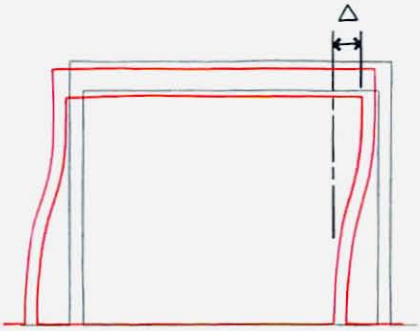


FIGURE 2-8. INTERSTORY RELATIVE DISPLACEMENT OF THE DYNAMIC STRUCTURE.

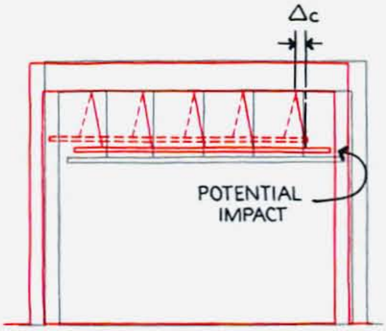


FIGURE 2-9. DISPLACEMENT DUE TO COMPONENT VIBRATION.

In addition to these two basic types of relative displacements, there are several types of relative displacements that may occur due to a combination of the two basic types. (Note that in the accompanying figures, all displacements are exaggerated so that the causes of different displacements are readily apparent).

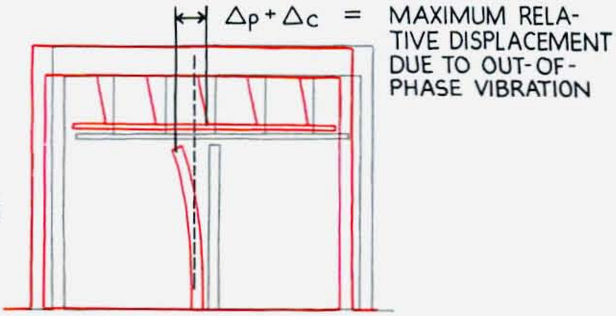


FIGURE 2-10. RELATIVE DISPLACEMENT BETWEEN TWO COMPONENTS DUE TO OUT-OF-PHASE COMPONENT VIBRATION.

3) Relative displacement between two components due to out-of-phase component vibration. At a point in time when the Dynamic Structure is in its undisplaced position, two components may still be displacing due to their own vibratory motions. In this case the components will be displaced relative to each other a distance equal to a maximum of their original distance apart (if any) plus the sum of their displacements caused by vibration (Figure 2-10).

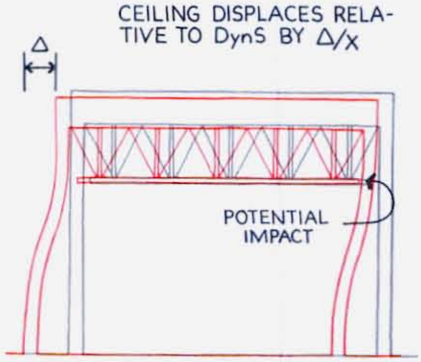


FIGURE 2-11. RELATIVE DISPLACEMENT BETWEEN A COMPONENT AND THE DYNAMIC STRUCTURE DUE TO INTERSTORY RELATIVE DISPLACEMENT.

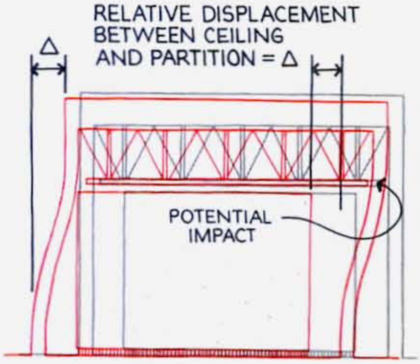
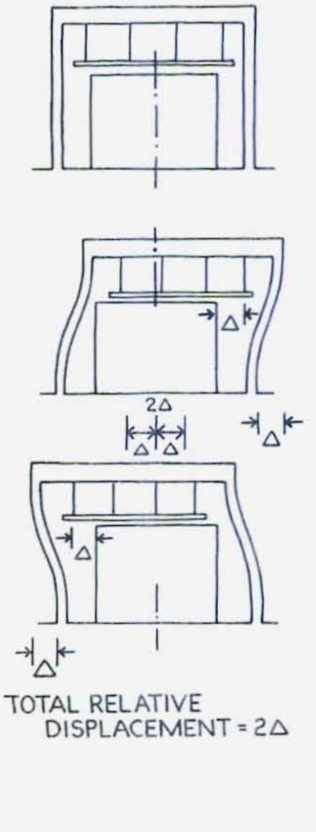


FIGURE 2-12. RELATIVE DISPLACEMENT BETWEEN TWO COMPONENTS DUE TO INTERSTORY RELATIVE DISPLACEMENT.



4) Relative displacement between a component and the Dynamic Structure due to interstory relative displacement. When a component of the Dynamic Structure displaces due to interstory relative displacement, any component anchored to that component of the Dynamic Structure will also displace. In some cases the concurrent displacement of the two components may result in impact at their interface, causing damage. The maximum allowable displacement of the Dynamic Structure at its interface with the component is then equal to their original distance apart (Figure 2-11).

5) Relative displacement between two components due to interstory relative displacement. Each of two components may be anchored to different components of the Dynamic Structure. If the Dynamic Structure experiences interstory relative displacement, then each component will move with the component of the Dynamic

Structure to which it is anchored. If the two components are anchored, one to the upper floor and one to the lower, then their relative displacement is maximum and equal to the interstory relative displacement (Figure 2-12). The architect must design the components for this displacement in either direction. Thus, he must design for the interstory relative displacement in both horizontal directions, whereas the structural engineer need design the Dynamic Structure only for the interstory relative displacement.

See margin diagram p. 79

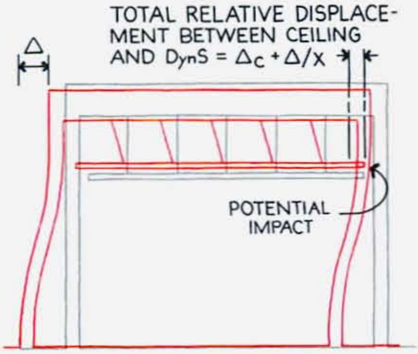


FIGURE 2-13. RELATIVE DISPLACEMENT BETWEEN A COMPONENT AND THE DYNAMIC STRUCTURE DUE TO CONCURRENT INTERSTORY RELATIVE DISPLACEMENT AND COMPONENT VIBRATION.

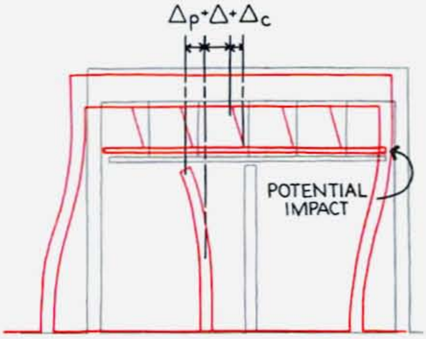


FIGURE 2-14. RELATIVE DISPLACEMENT BETWEEN TWO COMPONENTS DUE CONCURRENT INTERSTORY RELATIVE DISPLACEMENT AND COMPONENT VIBRATION.

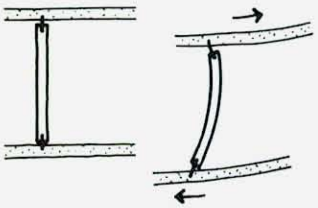
6) Relative displacement between a component and the Dynamic Structure due to concurrent interstory relative displacement and component vibration. In some cases a component may deform due to vibrational motions at the same time that it is subjected to interstory relative displacement. Such a condition is likely in relatively flexible buildings. If a component and the Dynamic Structure are moving away from each other, the relative displacement between the two will be a distance equal to the original distance between them (if any), plus a proportion of the interstory relative displacement, plus the out-of-phase displacement of the component as it deforms. If the component and the Dynamic Structure are moving toward each other, the distance required to prevent damage will be equal to a proportion of the interstory relative displacement at that location plus the displacement of the component due to its vibration (Figure 2-13).

7) Relative displacement between two components due to concurrent interstory relative displacement and component vibration. In perhaps the most potentially damaging condition, two components may be displaced relative to each other both by their attachment to two different components of the Dynamic Structure and by their own deformation due to vibratory motions. This situation is quite typical of flexible buildings: the structure deflects due to interstory relative displacements and this deflection in turn sets various components into their own vibratory motions. In the most extreme case, the Dynamic Structure will be deflecting in one direction, pulling a component with it, which will deflect due to its own vibration, and a second component may be deflecting in the opposite direction due to its own vibrational characteristics (Figure 2-14).

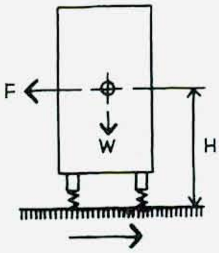
The above discussion of relative displacements treats them as if they occur in a two-dimensional plane. Because buildings are subjected to motions from many directions, relative displacements will also occur in many directions for any given component. Interstory relative displacements in three-dimensions were discussed in Chapter One and illustrated by Figures 1-20, 1-21, and 1-22. All relative displacements between components can be measured in a similar manner. However, for design purposes, one may describe any relative displacement in terms of displacements in two perpendicular planes. For instance, a two-dimensional analysis such as the ones presented above can be made for a component with respect to each of the two axes of a building and the two analyses combined to provide design criteria for the component's potential relative displacements. Chapter Four will illustrate this technique for ceiling systems and partitions.

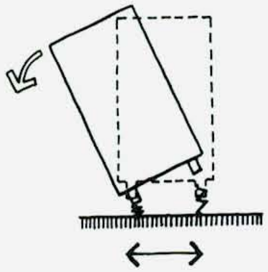
VIBRATIONAL EFFECTS: DESIGNING COMPONENTS FOR OVERSTRESS AND INSTABILITY

As the Dynamic Structure vibrates in response to input ground motions, Coupled and Uncoupled Elements will vibrate in response to the input motions of their Dynamic Environments. The general causes of damage due to vibrational effects are overstress, instability, excessive deflections, and impact of adjacent elements. The latter two causes have been discussed in the previous section because one must worry about the relative displacements of components due to vibrational effects. Overstress and instability are described more specifically below, and methods for designing components for these effects will follow.



- Overstress. As a building vibrates due to earthquake motions, flexural, shear, and axial stresses are induced in its components and connections. If these stresses exceed allowable values, damage results. The margin diagram illustrates an example of shear overstress resulting in anchorage failure, which is a frequent cause of damage in buildings.





- Instability. Components that are inadequately anchored are subject to toppling or falling. Instability exists when the seismic overturning force exceeds the gravitational restoring force. Sometimes instability results in damage to components when they slide from their original position.

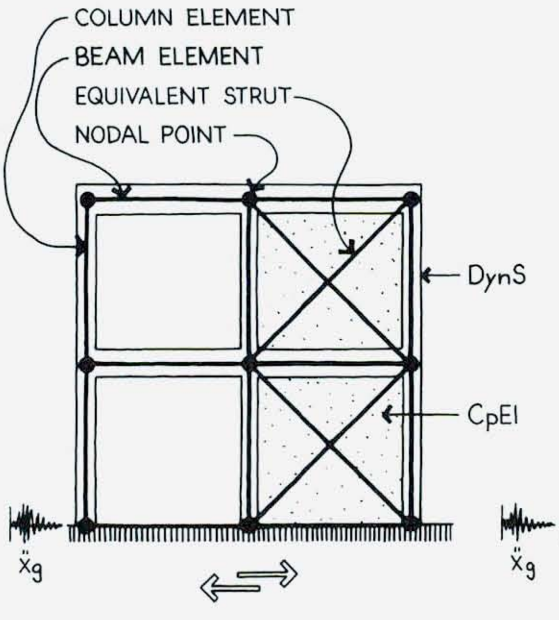


FIGURE 2-15. SIMPLIFIED ANALYTICAL MODEL FOR ANALYZING VIBRATIONAL EFFECTS ON COUPLED ELEMENTS.

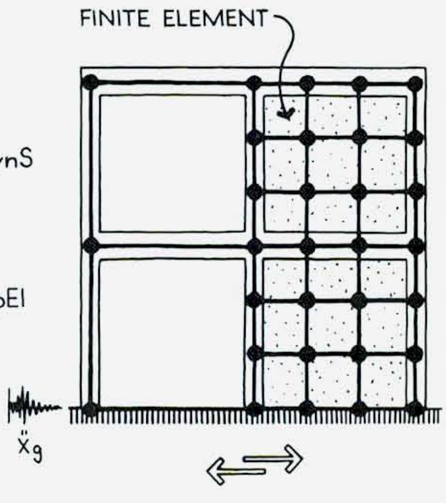


FIGURE 2-16. "EXACT" ANALYTICAL MODEL FOR ANALYZING VIBRATIONAL EFFECTS ON COUPLED ELEMENTS.

ANALYZING VIBRATIONAL EFFECTS ON COUPLED ELEMENTS

Coupled Elements must be analyzed in conjunction with the Dynamic Structure. Various analytical models exist for performing this task and they vary in their complexity. Figure 2-15 shows a simple analytical model in which columns and beams are represented by elements that interconnect nodal points. Enclosure walls are represented by "equivalent" struts. Figure 2-16 shows a somewhat more detailed model where beams and columns are represented by conventional beam and column structural elements, but the enclosure walls are represented in more detail by "finite elements." Although this latter approach is more complex, it more accurately represents the characteristics of the wall and the distribution of stresses within it. The analytical model developed and used depends upon the particular type of building and the amount of detail required.

ANALYZING VIBRATIONAL EFFECTS ON UNCOUPLED ELEMENTS WITH ONLY ONE CONNECTION TO THE DYNAMIC STRUCTURE

Figure 2-17 demonstrates the basic steps involved in analyzing Uncoupled Elements with one connection to the Dynamic Structure. First the Dynamic Structure is analyzed without including the physical presence of the Uncoupled Element (Figure 2-17a). This analysis will yield, among other results, the motions of the Dynamic Structure to which the component will be subjected, or in this case, the acceleration of the second floor, $\ddot{X}_2$ (Figure 2-17b). Then the Uncoupled Element can be analyzed by means of any of a number of approaches, depending on its dynamic characteristics. The basic property that determines the type of approach is the stiffness of the component: those components whose fundamental period of vibration is less than about 0.03 to 0.05 seconds are generally considered "rigid," and those with periods above this range are generally considered "flexible."

Vibrational Effects on Rigid Uncoupled Elements

The rigid component shown in Figure 2-17c can be analyzed or designed for the peak acceleration of the floor on which it is mounted, $\ddot{X}_{2(max)}$. This maximum acceleration is used to obtain the design force:

$$f=(\ddot{X}_{2(max)}) \times (M_{UncEl})$$

This approach is valid because the component is rigid, and, hence, the motions of the floor are not amplified by the response of the Uncoupled Element.

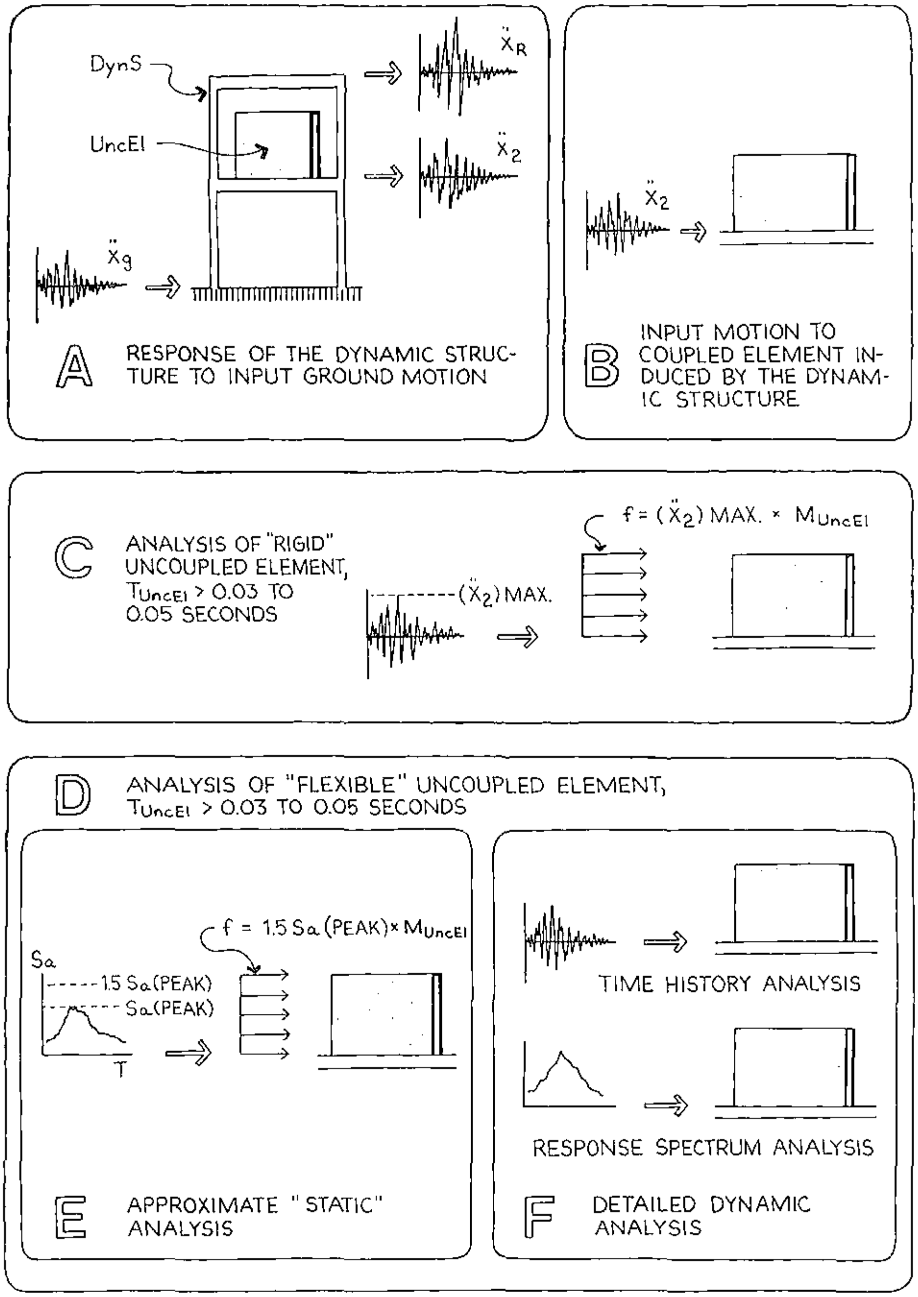


FIGURE 2-17. INVESTIGATIVE PROCEDURE FOR VIBRATIONAL EFFECTS ON UNCOUPLED ELEMENTS WITH ONLY ONE CONNECTION TO THE DYNAMIC STRUCTURE.

Vibrational Effects on Flexible Uncoupled Elements - Approximate "Static" Analysis

To analyze the flexible Uncoupled Element in Figure 2-17d, two approaches are possible. The first is an approximate "static" analysis, in which the component can be designed for an acceleration equal to a factor times the peak of the floor response spectrum, $S_{a(peak)}$ (Figure 2-17e). The factor (1.5 in this example) is based upon factors similar to the "ZIS" portion of the 1976 Uniform Building Code requirements for "lateral force on elements of structures." The 1.5 factor is typical of conservative procedures for designing components in nuclear power plants. In this approach the applied force is equal to a static coefficient times the weight of the Uncoupled Element:

$$f = 1.5(S_{a(peak)}) \times (M_{UncEl})$$

This approach accounts for dynamic amplification in an approximate manner, and can be used if the frequencies of the Uncoupled Elements are not calculated; it will ensure a conservative, safe design. The advantage of the approach is that the frequencies of the Uncoupled Element do not have to be calculated, but the disadvantage is that the seismic loads thus calculated may be quite high.

Vibrational Effects on Flexible Uncoupled Elements - Detailed Analysis

If the design team desires a more precise analysis than the one outlined above, detailed dynamic analysis procedures must be employed. Figure 2-17f shows schematically the two possible approaches: time history dynamic analysis and response spectrum dynamic analysis. Both of these procedures must be performed by the structural engineer and require computer and engineering time; the response spectrum method is somewhat more economical to use because it requires less engineering and computer time, but the time history method may result in lower calculated response.

ANALYZING VIBRATIONAL EFFECTS ON UNCOUPLED ELEMENTS WITH TWO OR MORE CONNECTIONS TO THE DYNAMIC STRUCTURE

The Uncoupled Element in Figure 2-18b is a typical example of a component connected to two or more separate points on the Dynamic Structure. Both flexible and rigid components in this category may be analyzed by one of two approaches, either detailed or static.

Detailed Analysis

The analytical model for this approach is shown in Figure 2-18c. In this case the analytical model is subjected to a time-history analysis that uses as input the motions at the two different supports of the Uncoupled Element.

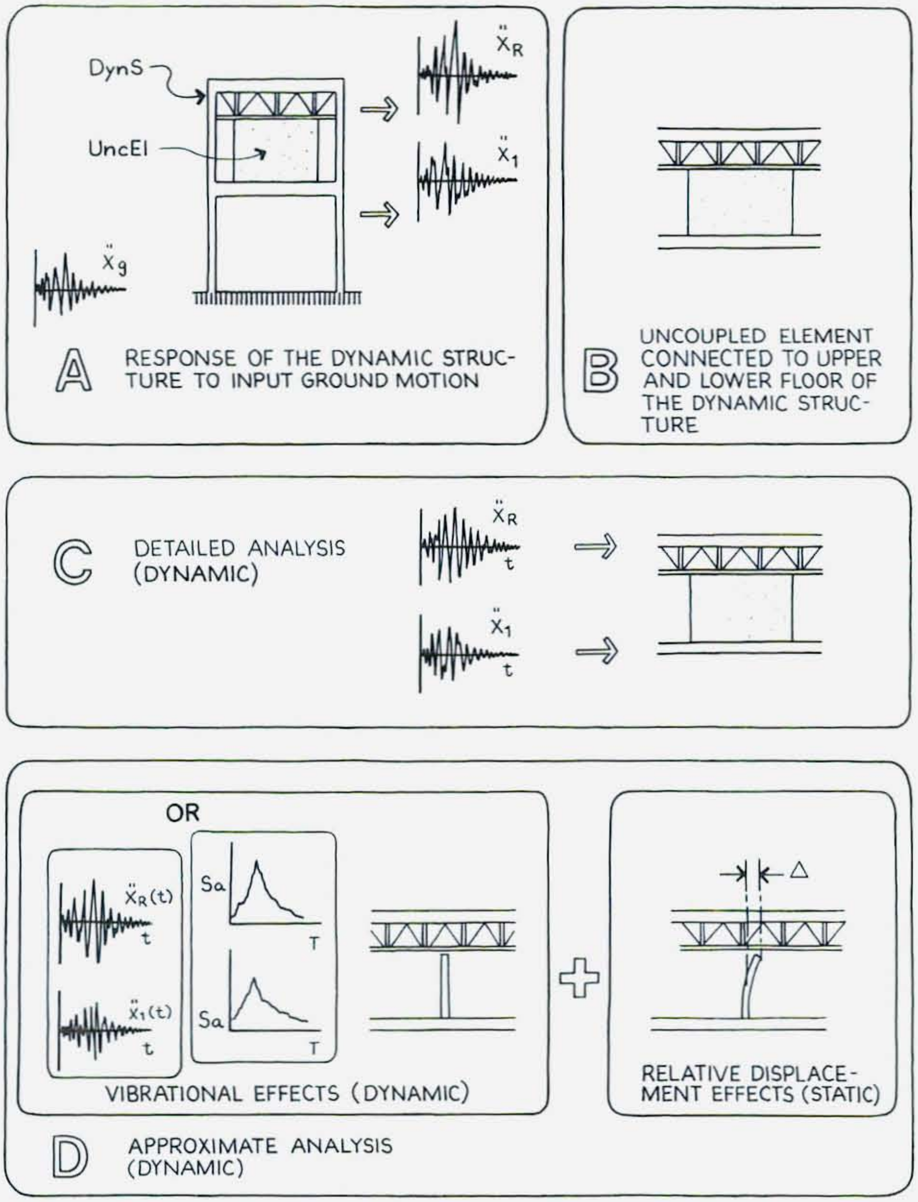


FIGURE 2-18. INVESTIGATIVE PROCEDURE FOR VIBRATIONAL EFFECTS ON UNCOUPLED ELEMENTS WITH TWO OR MORE CONNECTIONS TO THE DYNAMIC STRUCTURE.

Approximate Analysis

In this approach the motions of the Uncoupled Element are approximated by superimposed vibrational effects and relative displacement effects, as shown in Figure 2-18d. First, relative displacement effects are accounted for by statically displacing the Uncoupled Element by an amount, Δ, which is the maximum relative displacement of the two different supports. The Coupled Element is subjected to different static support displacements and a static structural analysis performed to determine the internal forces (moments, shears, and so forth). The results are then superimposed upon the results of a time history dynamic analysis or a response spectrum dynamic analysis. This procedure is an approximation, but has the advantage that it can be readily applied in the analysis of enclosure and finish systems.

SUMMARY

This chapter has introduced a Dynamic Model for the design of buildings and building components according to dynamic principles. The basic factors determining a component's dynamic role were defined, as well as the conditions under which that role may change. The Dynamic Model was also discussed in terms of its effects on the design process for both buildings and building components. Finally, the different means of determing quantitatively the Dynamic Environment for building components were presented. Chapters Three and Four which follow apply the concepts of the Dynamic Model and the Dynamic Environment to the design of specific building components.

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Chapter Three

Building Response and Component Design: An Enclosure Wall Case Study

The effect of the Dynamic Model on the design process can be demonstrated best by an analysis of its use in the design and construction of a building. During research conducted under an earlier National Science Foundation grant, McCue Boone Tomsick's (MBT) research team had the unique opportunity of working with a design team which could test the theory's usefulness in the design of an enclosure wall system. At that time, MBT was engaged in a commission for the IBM Corporation to design a building complex of 600,000 square feet which would accommodate over two thousand people. Although specific aspects of the Dynamic Model had not yet been developed, the basic concepts had been for-

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mulated, making it possible for the design team to utilize them in the design of the IBM facility. The case study that follows summarizes important steps in the application of the Dynamic Model to the overall design of the building, and then presents the design of the enclosure wall as an Uncoupled Element for its particular Dynamic Environment.

The subsequent analysis follows the major steps of the design process as outlined in Chapter Two, beginning with programming considerations, proceeding through site analysis, overall building concepts, and concluding with the design of the enclosure wall system as one example of the use of the Dynamic Model for building component design. In order to present a clear and logical description of the design process, each step appears sequentially even though some retracing of steps occurred, as is typical in design projects. This case study demonstrates that various decisions made early in the design process can have a significant effect not only on the response of the building as a whole, but also on the design of building components for the seismic criteria of their Dynamic Environments.

PROGRAMMING

Program requirements for the IBM facility called for the provision of almost two thousand individual offices, a large computer center, a library, classrooms, and a food service facility. In addition, the office space had to be able to accommodate specific uses at initial occupancy, but remain adaptable for anticipated future changes in the client's functional requirements at the site. Good communication and direct access between key functions were the major requirements for circulation.

In terms of earthquake considerations, life-safety was the high priority, with the importance of continued operation and protection of capital investment serving as major secondary criteria. Of critical importance in terms of operation and investment was the computer center, which would be very sensitive to differential settlements and lateral movements. Very early in the design process, *The design would require a sophisticated blend of design and seismic criteria.*

therefore, the architects and engineers were aware that a sophisticated blend of design and seismic considerations would be required to provide the design quality, life-safety, and operational and financial protection desired by the owner.

SELECTION OF SITE LOCATION

As the first step in the site analysis procedure, MBT conducted a study of the feasibility of development on the site which IBM tentatively selected. The site is located in the seismically active Northern California region, approximately ten miles northeast of the nearest trace of the San Andreas fault, and six miles southwest of the Calaveras fault (Figure 3-1).

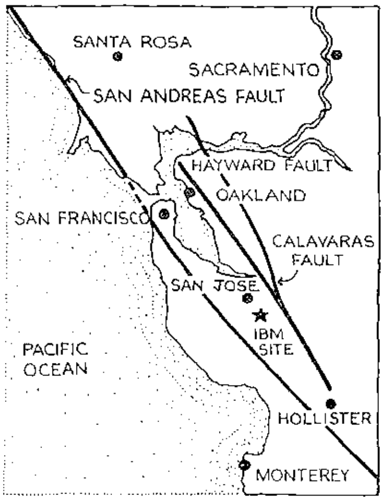


FIGURE 3-1. SITE LOCATION RELATIVE TO MAJOR FAULTS

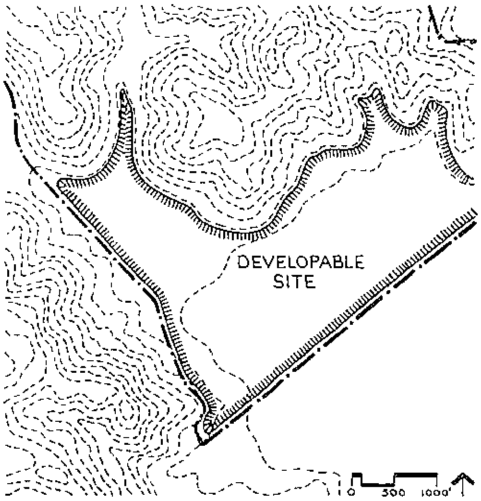
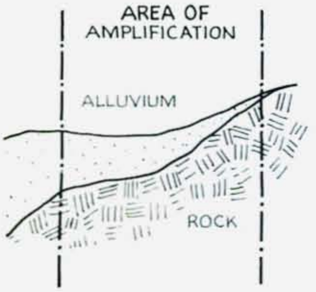


FIGURE 3-2. DEVELOPABLE SITE.

Lowney-Kaldveer Associates, the soils engineers, were informed of the intended use of the site and the likelihood of low- to medium-rise building development. They performed a preliminary soils investigation which, in combination with program requirements, determined preliminary design criteria for building siting, earthwork, and foundations. In addition to these criteria, the investigation revealed the following conditions requiring special design consideration:



- an upper, three to ten foot thick layer of moderately expansive silty clay which would require special treatment to prevent heave and resulting damage to structures;
- a relatively high water table which, under hydrostatic pressure, would cause construction problems during excavation for deep foundations;
- likely amplification of seismic waves in the area of transition between alluvial plain and hills where rock is close to the surface; thus, buildings should not be located adjacent to the base of the hills.

In the portion of the site that was otherwise desirable for development (Figure 3-2), a fault location study identified a fault passing beneath the alluvium. The location of the fault was determined by magnetometer and seismic refraction surveys, and the width of the fault trace was measured to be forty feet. The fault was considered potentially active, based on geological formations and indication of activity along other portions of the same fault. The soils engineers recommended a fifty-foot offset on either side beyond the forty-foot wide fault trace, resulting in a 140 foot wide restricted zone. The land within this restricted area did not meet the engineer's design criteria for location of structures; therefore, greenbelt, parking, recreation and roads were recommended as alternative uses. Taking into acacount the configuration of the site and the location of the fault, the architects considered alternative site plans which would accommodate the desired relationships between building and parking. Since the fault trace roughly bisects the buildable site area, alternative locations fell to one side of the fault or the other. Alternative C (which placed the project to the east of the fault zone and just south of the hills) was recommended because it allowed a large buildable area, maximum advantages under zoned height requirements, efficient road access, a substantial, landscaped buffer zone, and accommodation of storm drainage requirements.

DETERMINATION OF GROUND RESPONSE DATA

Once the site was determined to be feasible for development, a seismic response analysis was performed to determine the probable characteristics of ground input motion for the chosen location on the site. The method the soils engineers utilized involved:

1) establishing an idealized soil profile at the site from test borings and laboratory test results;
2) selecting design earthquakes for the site by predicting the magnitude and dynamic characteristics of possible future earthquakes;
3) modifying available records of bedrock motions so that the ground surface accelerations could be determined;
4) analyzing the dynamic response of the soil deposit to the anticipated bedrock motions to determine ground surface accelerations.

An idealized soil profile was developed using data from the borings of preliminary and final soils investigations. Then seven earthquakes of various magnitudes and origins were selected by Lowney-Kaldveer for study for the IBM site. Their magnitudes varied from 5.25 to 8.25 on the Richter Scale, and their probability of occurrence ranged from 25-50 years to 500 years up, with the smaller magnitudes having the more frequent occurrence intervals. For each of the seven earthquakes a source accelerogram was chosen. Because accelerograms of the magnitude and location needed were not available (as is often the case), appropriate existing records were adjusted for magnitude and source. Since there was no existing record which corresponded to the largest of the seven earthquakes (8.25 on the San Andreas fault), a synthetic source accelerogram developed at the University of California at Berkeley was used to simulate an earthquake of such magnitude.

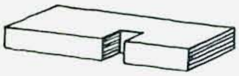
Once the source accelerograms were chosen, they were then adjusted for the distance of the site from the epicenters of the seven earthquakes. This procedure resulted in bedrock accelerograms for the site of the building. Based upon these accelerograms and the soil profile, ground motion accelerograms for the surface of the site were developed using a computer program (SHAKE) which takes into account the dynamic characteristics of

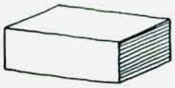
Amplification of bedrock motions would be likely due to the stiff nature of the soil materials and their limited thickness.

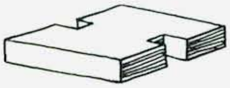
the soil materials overlying the bedrock. The natural period of the soil deposit was low, ranging from approximately 0.5 to 0.8 seconds for the seven earthquakes studied. Bedrock and ground surface acceleration were high due to the site's location close to major faults, a characteristic of most of the surrounding area which could not be avoided in site selection. Amplification of the bedrock motion was found in all seven earthquakes studied, primarily because of the very stiff nature of the soil materials and their limited thickness. The ground motion accelerograms were then used to construct response spectra for each of the seven earthquakes for damping values of two, five, and ten percent. The response spectra would then serve as the basis for design, since they record the maximum acceleration to be used for a building of known period of response.

BUILDING DESIGN ALTERNATIVES

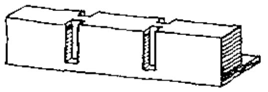
While the ground response data were being prepared, conceptual building designs were also being developed. Then each concept was evaluated on the basis of its functional program (space requirements, services, circulation, and adaptability to future change), construction and maintenance costs, aesthetic and psychological factors, and approximate seismic response. Nine different concepts which represented the prototypical solutions to the problem were considered (See marginal diagrams). Three of these concepts, 1A, 3A, and 7C were selected for further study. Several options for the structural system were considered for each of the three schemes: steel moment frame, steel braced frame, concrete shear wall, ductile concrete moment frame, and ductile concrete tube frame. Most of the concrete systems were eliminated for the following reasons:



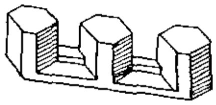




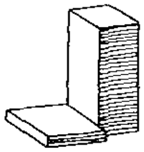
- a concrete ductile moment resisting frame would result in a higher cost for the structural system than steel for all schemes;
- concrete shear walls in the building cores were considered unfeasible for eight-story schemes because they would generate very large overturning moments;

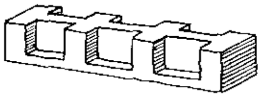


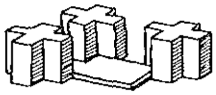
- concrete tube frame solutions were considered unfeasible because they would interfere with program requirements, especially the large continuous space at the ground floor.



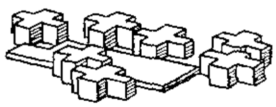
On the basis of these considerations, steel framing was recommended with the exception of scheme 7C, which at this point also appeared feasible with a concrete system incorporating shear walls only at the central cores.







From the three alternatives, schemes 3A and 7C were selected for more detailed analysis. Scheme 3A (Figure 3-3) was a rectangular-plan, three-story concept which achieved the desired qualities of adaptable space and a simple and economic structure. Scheme 7C (Figure 3-4) consisted of a large ground floor of continuous adaptable space with a series of eight, three-story, cruciform buildings which provided windows for over sixty percent of the individual offices on those floors, satisfying the owner's desire to maximize views of the exterior environment. Spatial configurations were further developed, tentative material and structural systems were examined, and detailed cost comparisons were made for each scheme with its possible structural systems.



At this stage in the design process, the dynamic role of other building components was considered. Each building concept was examined to determine which components might logically become part of the Dynamic Structure, which would be Coupled Elements, and which Uncoupled Elements. These dynamic role designations were used as a basis for preliminary estimates of building response and to assist in the projection of comparative construction costs.

The enclosure wall was determined to be unsuitable for incorporation into the Dynamic Structure because it did not extend to the ground at all facades, but stopped at the roof of the first floor, a discontinuity which ruled out the possibility of the wall increasing the structure's ability to sustain seismic loads. Considering the dynamic role analysis and the functional and aesthetic aspects of the two schemes, the owner and the design team agreed to proceed with scheme 7C. This scheme

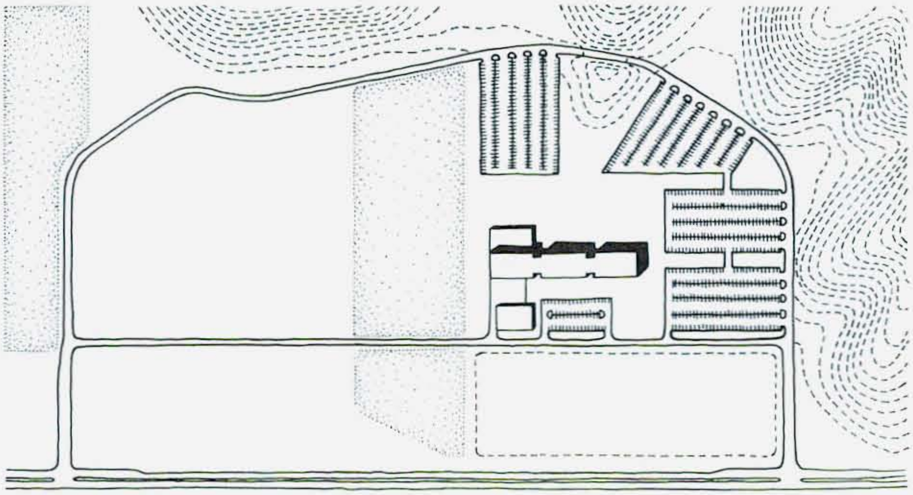


FIGURE 3-3. SCHEME 3-A/SITE PLAN

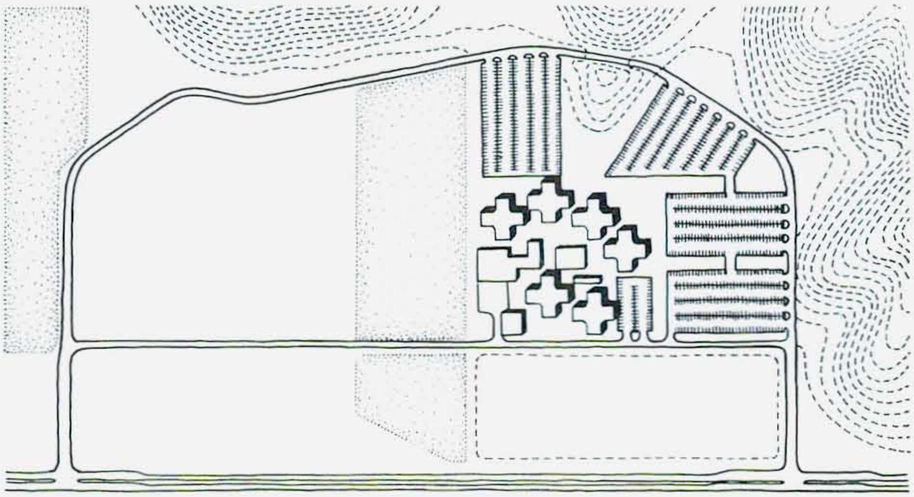


FIGURE 3-4. SCHEME 7C/SITE PLAN

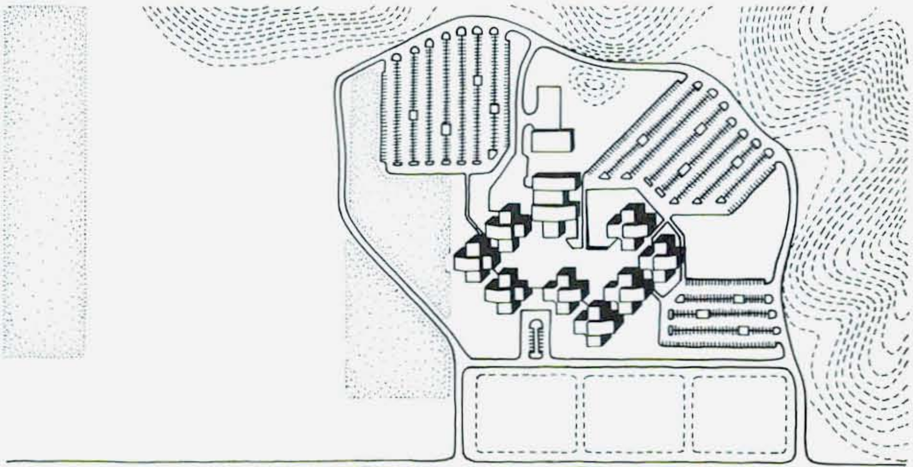


FIGURE 3-5. SCHEME 7E/SITE PLAN.

then underwent several phases of additional refinement with minor variations in plan form and story heights, and was finally approved under the designation 7E, as illustrated in Figure 3-5.

DESIGN DEVELOPMENT AND STRUCTURAL CONCEPTS

During design development of scheme 7E, both steel and concrete structural systems were studied in more detail to determine the most appropriate roles of various building components. The systems were then evaluated for their compatibility with the functional program, construction scheduling and cost considerations, aesthetic design quality, and response to seismic loads. Two structural alternatives were determined to be most viable:

- ductile steel moment resisting frame;
- concrete shear wall utilizing the cores of the cruciform-shaped buildings.

The concrete system had the advantages of no delay in the start of construction as would be required for the rolling schedule and delivery of steel, and no requirement for expansion joints between the plaza framing system and the retaining walls. But the steel moment frame was selected for the following reasons:

A ductile steel moment resisting frame would make it possible to avoid coincidence of ground and building periods.

- The response spectra developed generally peaked at .4 to .6 seconds, meaning that the structural system should have the relatively longer periods possible with ductile steel moment resisting frame structure but not with a concrete one. Otherwise coincidence of ground and building period would occur, causing resonance.
- Because of the weight of concrete, design seismic forces for concrete would be four times those for steel.
- Concrete has less reserve energy capacity than steel.
- The scheme 7E plan configuration made it difficult to resolve diaphragm shear forces in concrete.
- The weight of the concrete would require a more ex-

pensive and complex foundation system, whereas the steel moment frame could be supported on conventional, spread footings.

- A standard two-way waffle slab system would not be feasible for the floor plan configuration, and other concrete framing systems would be too costly.
- Interior space planning options in the computer center would be severly restricted due to the shear walls in the three-story buildings above the computer center.

Concrete shear walls would interfere with space planning and mechanical system layout.

- Shear walls would interfere with the mechanical distribution system since they would be located at the cores where the greatest concentration of mechanical systems would also occur.

PROJECTION OF BUILDING RESPONSE

For scheme 7E the first mode of vibration was dominant.

Once the basic steel moment frame concept was established, Forell/Elsesser Engineers performed a preliminary structural analysis for the building, using hand calculations and in-house computer runs. These calculations established preliminary member sizes and stresses, as well as interstory drift and the fundamental period of the building. The engineers then used the building's period, calculated to be 1.0 seconds, in conjunction with the response spectra developed earlier, to determine the building's probable response. In the case of scheme 7E, the first mode of vibration was dominant because the buildings were relatively short (four stories) and thus modal superimposition did not lead to higher stress levels. The maximum acceleration computed from the response spectra substantially exceeded existing recommended code forces because of the large amplification of base rock motion due to the nature of the overlying soils. But since structures behave inelastically during major earthquakes, the response spectrum that assumes elastic behavior is incorrect, and yields maximum accelerations higher than actually occur for these quakes. As the structure goes into inelastic behavior, the damping values increase and the period lengthens, which in the case of the IBM building would decrease the seismic response. Hence, the structural engineers took this reduction into account when designing for the severest probable earthquake and the severest possible earthquake. They performed a three-dimensional computer analysis on mathematical models of the buildings. Damping, ductility, and reserve energy of the structure were taken into consideration. The response spectra for the two major earthquakes considered most probable were smoothed, and a ductility factor μ = 4 and damping of 5% were used in order to determine the appropriate design level, which was found to be 15% g. For the building's period of 1.0 seconds, this level was considerably higher than the 1976 Uniform Building Code requirements of 7% g and the Applied Technology Council's tentative recommendations of about 11% g, and was nearly as great as the California Hospital's Title 17 requirement of almost 16% g (Figure 3-6). Such a high lateral force coefficient was warranted because the site had the potential for large amplification of seismic waves due to its sloping rock-alluvium soils condition (described earlier) and the fault which passed through the site. For the largest credible earthquake, a ductility factor of μ = 8 and 10% damping were used. The large ductility capacity of the steel moment building was judged to be able to sustain the structure against collapse in the event of the largest credible earthquake.

The design level was 15% g.

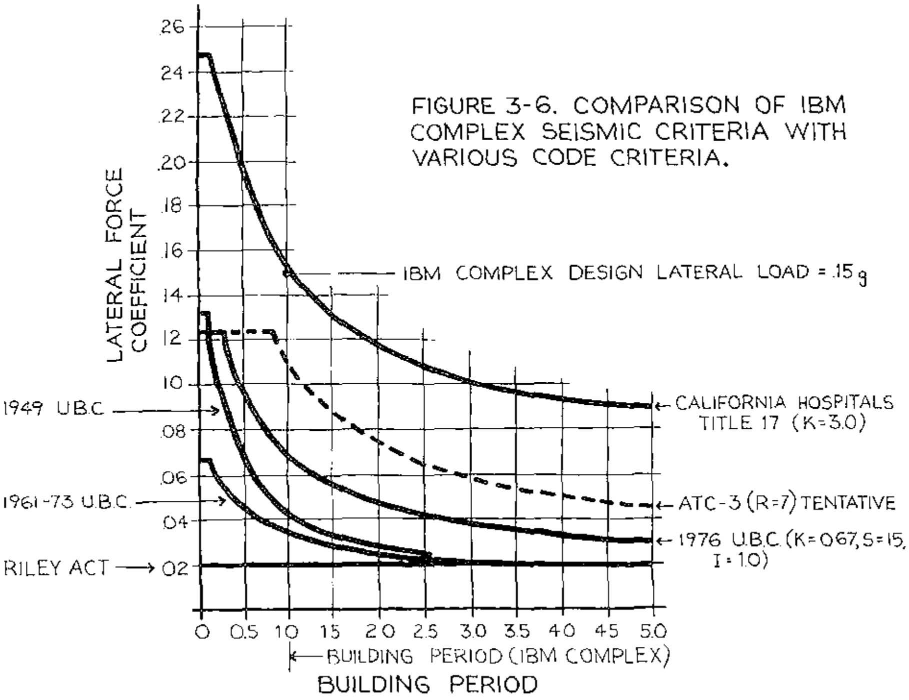


FIGURE 3-6. COMPARISON OF IBM COMPLEX SEISMIC CRITERIA WITH VARIOUS CODE CRITERIA.

The campus-like plan led to some seismic engineering complexities.

The owner's choice of a scheme incorporating a campus-like complex rather than a monolithic block-like structure led to a complex relationship of building shapes, which presented some difficulties from a seismic engineering point of view. The design consisted of a series of four-story buildings linked to a one-story computer facility in an arrangement which, becuase of its projecting wings, re-entrant corners, and asymmetrical plan, might, during an earthquake, cause parts of the building to vibrate out-of-phase, resulting in torsional forces and stress concentrations. To overcome these potential problems, the building complex was broken into smaller, less complex elements by the use of seismic expansion joints. The result was four biaxially symmetrical buildings of four stories, and three different building types with one axis of symmetry (Figure 3-7). In the larger buildings, the column stiffnesses at the lower floor were carefully adjusted to make the seismic resistance of the large first floor compatible with the smaller individual buildings above. Rotational torsion in the unsymmetrical direction was also accounted for in the design.

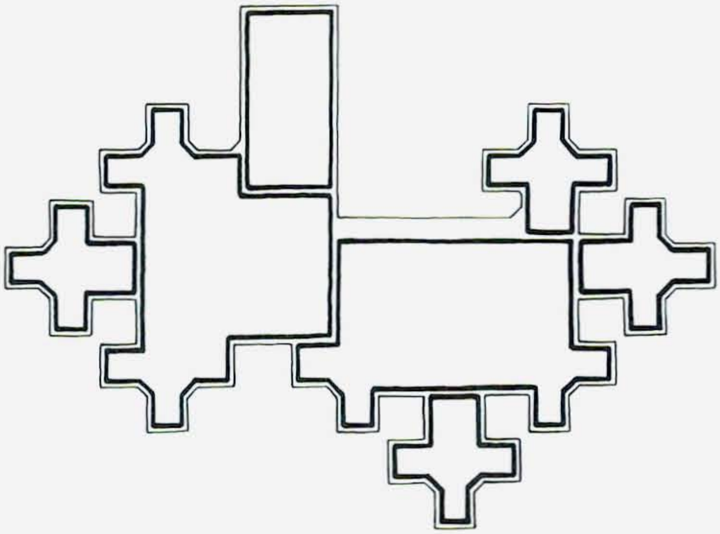
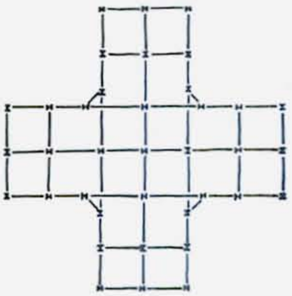


FIGURE 3-7. SECTIONS OF BUILDING COMPLEX DYNAMICALLY SEPARATED BY SEISMIC EXPANSION JOINTS.

For aesthetic reasons, the architects wanted the framing system to utilize a cantilever system at the ends of the bays of each cruciform building. Such framing would have allowed a continuous band of glass uninterrupted by



the column around the outer faces of the cruciform buildings (See marginal diagram). After preliminary analysis, however, this scheme was abandoned in favor of the selected framing scheme, because of significant additional costs and the potentially larger deflections under seismic loads resulting from the less efficient lateral resisting system.

FINAL LATERAL ANALYSIS

The final lateral analysis to determine building response was made using a computer program, XTABS, in which the building is idealized by a system of independent frames interconnected by floor diaphragms which are rigid in their own plane. The program is three-dimensional in the sense that it computes translations at each floor in both axes, as well as rotation about the vertical axis. In addition, at each column, the vertical displacement and rotation is computed. Input data for the analysis consisted of the following:

- building member description: the moment of inertia, shear area, dimensions, and modulus of elasticity of each building member;
- building member location: the location of each member within the building in terms of x, y, and z coordinates from a basic reference point;
- loads: dead loads and live loads as well as the 15% g lateral load.

Building response was used to determine the Dynamic Environment for Coupled and Uncoupled Elements.

Given the above data, the XTABS computer run determined bending and axial forces for each member, deflections in terms of displacements from the vertical axis at all floors, and mode shapes. The highest deflection occurred for the dead plus live plus seismic loading condition, with a maximum interstory drift of about .75 inches. This loading situation also applied to all other frames at all other floors in the various building types. The building response, as determined by the data from the XTABS program, was used, in turn, to determine the Dynamic Environment which provided the design criteria for Coupled and Uncoupled Elements, including the enclosure wall system of this study.

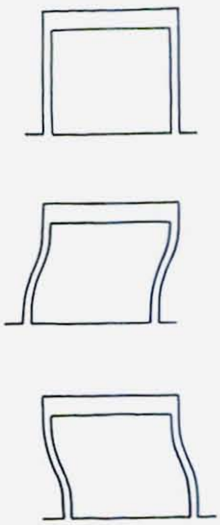
DESIGN STRATEGY FOR THE ENCLOSURE WALL

The owner's objectives for the design of the exterior wall were that it be designed for an optimum balance of aesthetics, cost, and function, and that the materials used be of the type requiring little or no maintenance. Additional requirements developed by the design team expressly for seismic considerations were the importance of continued operation of the building, the protection of the contents from damage, and the minimization of replacement costs of the wall in the case of moderate to severe earthquakes. Based upon these general requirements, more specific seismic design requirements were developed as follows:

- The enclosure wall must respond to the Dynamic Environment imposed by the Dynamic Structure during an earthquake of moderate intensity in a manner such that almost no damage would occur.
- For the severest probable earthquake, the enclosure wall must accommodate interstory drift of the Dynamic Structure without a significant amount of anchorage, framing, or panel failure, with a low probability of major glass breakage, and with only a minor amount of deformation-caused leaking. In addition, the curtain wall must be designed to avoid the possibility of its damaging the Dynamic Structure.
- For the severest possible earthquake, the enclosure wall should respond to the input motions of the Dynamic Structure such that damage to it would be minimized in order to provide a high standard of life-safety for the occupants.

In this case only the Dynamic Structure should transfer motion to the enclosure wall.

Having established these requirements, it was then necessary to determine the specific Dynamic Environment for the enclosure wall. In this case, the design team determined that only the Dynamic Structure should transfer motion to the enclosure wall. The ceiling and partition systems were to have the capability of being relocated from time to time, making it impossible to determine their influence on the response of the wall, necessitating their separation from it, and hence removing them from the Dynamic Environment for the enclosure wall. The



magnitude of the building response was determined for the various frames, one through seven, in each of the x and y directions, at each floor level. The wall was to be designed such that its connections would sustain the highest acceleration determined by the computer analysis for the given design earthquakes. In addition, the largest interstory displacement or "drift" in any one story and frame location was used as a relative displacement criterion for the design of the entire enclosure wall system. From the XTABS output, the largest drift was found to be somewhat less than 3/4". Thus, the wall was to be designed to accommodate a plus or minus 3/4" drift between floors in any horizontal direction from the at-rest position without interference with the other design objectives, which had been developed as follows:

Thermal transmission: Overall "U" value should be .4 or less and the overall shading coefficient .35 or less.

Thermal movement: Within the audible range there must be essentially noiseless contraction and expansion, both vertically and horizontally, of component materials for a temperature range of 20° F. to 180° F. without buckling, opening of joints, glass breakage, or undue stress on fasteners.

Wind pressure: The wall must be designed for both flexural and torsional stress for the following positive and negative wind pressures acting perpendicular to all planes of the curtain wall/cladding elements: less than 30' - 15 psf; 30' to 49' - 20 psf; 50' to 99' - 25 psf.

Air Infiltration: Tested in accordance with NAAMM Standards, air infiltration should not exceed 0.06 cubic feet per minute per square foot of fixed unit area.

Light transmittance: Transmittance should not be less than 20%; shading coefficient with interior blinds should not be less than 0.30.

Water infiltration: Essentially no water penetration, that is, the appearance of uncontrolled water, should occur during NAAMM Standard tests.

Self-drainage: The wall must be designed to drain to the exterior any water entering at joints or glazing reveals and any condensation occurring within the unit's construction.

EVALUATION OF ALTERNATIVE ENCLOSURE SYSTEMS

At first it was uncertain whether the enclosure wall would be designed as a Coupled or an Uncoupled Element.

During the conceptual design phase, the design team determined that the enclosure system could not be incorporated in the Dynamic Structure, but it was uncertain whether the wall would be designed as a Coupled or an Uncoupled Element. Once the conceptual design scheme was chosen and the Dynamic Environment for the wall determined, the design team then decided to examine all feasible enclosure systems, both those which would be heavy and hence Coupled Elements, and those which would be light and hence Uncoupled Elements.

Two different concrete systems were studied. The first system consisted of prefabricated concrete panels anchored directly to the Dynamic Structure and spanning the full story height (Figure 3-8). This scheme was considered to be somewhat undesirable because the heavy mullions necessary to give the panels structural integrity would conflict with preliminary facade studies which had indicated that a continuous glazing system would be the most aesthetically pleasing. The second concrete system considered was composed of precast concrete wall spandrels between columns braced by a secondary steel subframe. In this case the windows would be treated as horizontal bands interrupted only by the precast column covers (Figure 3-9).

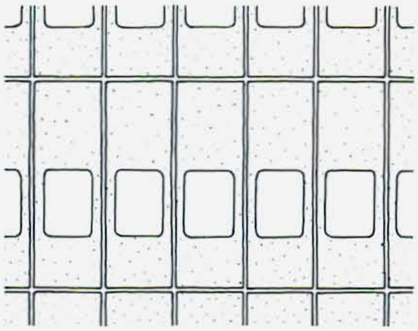


FIGURE 3-8. FULL BAY WIDTH, FULL STORY HEIGHT PANELS.

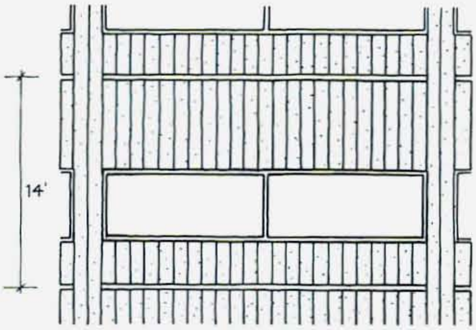


FIGURE 3-9. FULL BAY WIDTH, PARTIAL STORY HEIGHT PANELS.

Both concrete systems were eventually abandoned in favor of a metal system for several reasons. The difficulty of detailing concrete systems to accommodate the interstory drift of the structural frame was a primary consideration, because conventional joints between panels would not accommodate the large potential drift of the Dynamic Structure, and because shiplap type joints would be prohibitively expensive. In addition to detailing problems posed by interstory drift, the heavy weight of concrete panels, as opposed to metal panels, would in-

The weight of the concrete panels would cause two major problems.

crease the force level for which the building must be designed; since the design force levels were already high because of geological site conditions, designing the structure for even higher force levels would be extremely difficult and much more costly. The second disadvantage of the concrete panels' greater weight was that heavy equipment would be required for installation, an expensive venture and one likely to cause problems on account of the large number of small courtyards in which the panels would be installed, where large and heavy equipment would be virtually impossible to use. Thus, metal panels, which would be Uncoupled Elements and therefore have little effect on the performance of the structural system, were chosen.

Metal panels were chosen and would be Uncoupled Elements.

The design team began examining . . . subframes for attaching the panels to the structure.

Having chosen metal panels, which would be relatively lightweight, the design team examined various means of anchoring the metal panels to the structural system such that the large interstory drift could be accommodated. The design team began to examine metal enclosure system alternatives utilizing a subframe system, a common practice in curtain wall construction. A subframe system allows the use of smaller panels, thus reducing the difficulty and expense of detailing. The subframe serves as the structural support for the enclosure panels, and the structural system serves as the support for the subframe system. The various connections provide the capability for movement necessary for vertical and horizontal deflections.

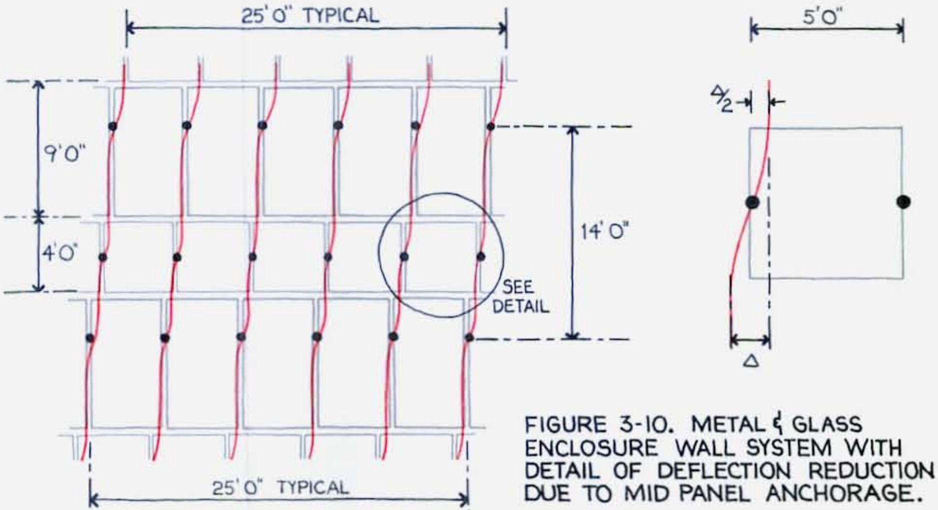


FIGURE 3-10. METAL & GLASS ENCLOSURE WALL SYSTEM WITH DETAIL OF DEFLECTION REDUCTION DUE TO MID PANEL ANCHORAGE.

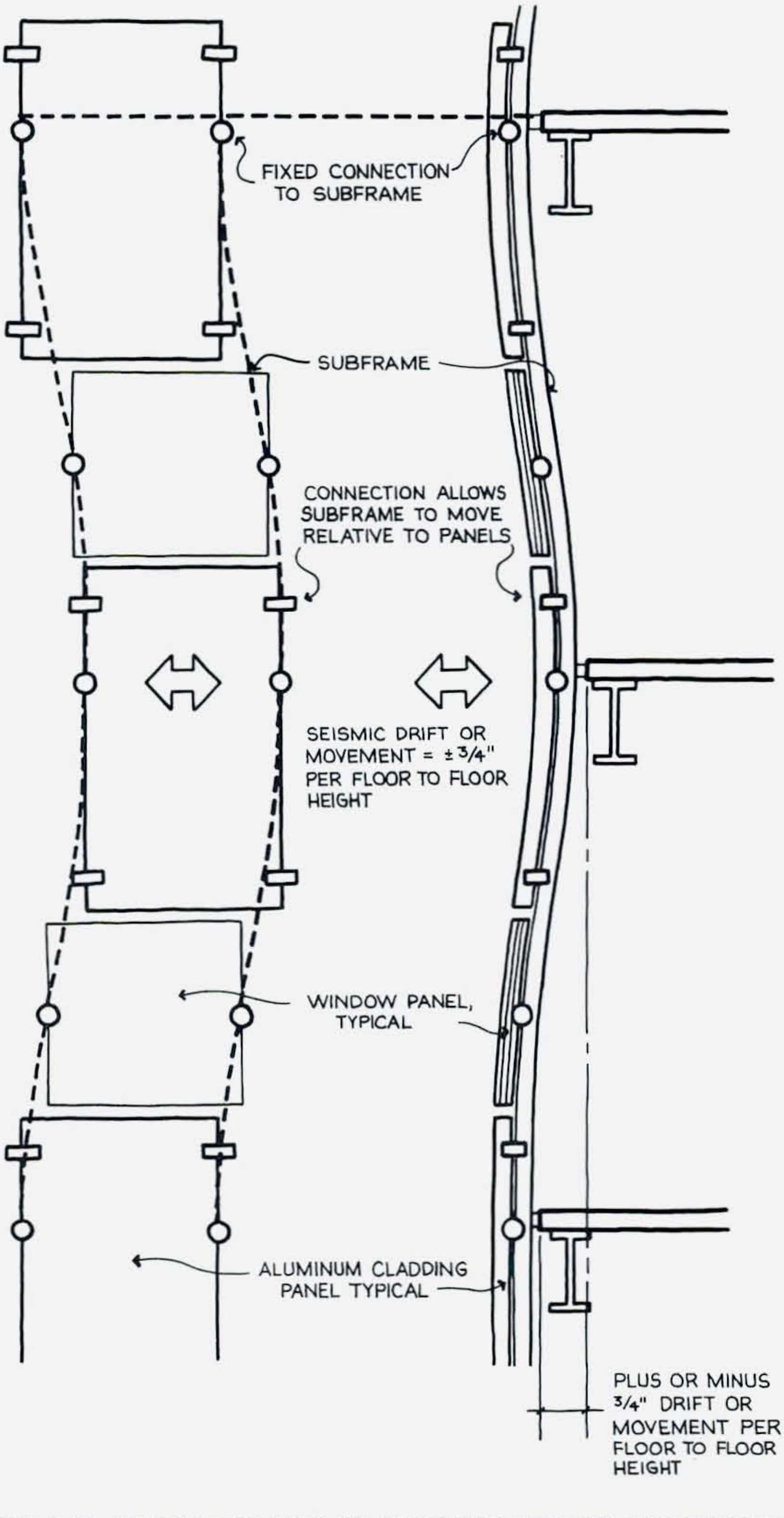


FIGURE 3-11. SCHEMATIC DETAILS SHOWING SEISMIC MOVEMENT OF METAL AND GLASS PANEL SYSTEM AS DESIGNED BY ARCHITECT AND ENCLOSURE WALL CONSULTANT.

The subframe system for anchoring panels was chosen essentially to make possible both the desired aesthetic treatment of the glass pattern and the accommodation of the relatively large interstory drift of ± 3/4 inch per story. While a subframe system is a commonly used method of supporting enclosure walls, the design of the anchorage of the panels to the subframe, and that of the subframe to the structure were, in the case of the IBM complex, unique. To the subframe system, a skin was anchored which consisted of single panels of metal and metal frame holding glass. Anchorage of each panel to the subframe was from its midpoint, thus reducing the amount of deflection that must be accommodated in any one direction by one-half (Figure 3-10). Anchors at midpoints of panels attached the panels to the subframe, while anchors at top and bottom permitted the subframe to move with respect to the panels up to ± 3/4 inch per story when necessary for the dynamic movement of the structure (Figure 3-11). In addition to the allowance for horizontal seismic drift, allowance for 1/2 inch of floor slab deflection was also designed in order to accommodate beam/building deflections. Building deflection (vertical) was accommodated in the cladding to window horizontal expansion joint. The following list presents the detailed design criteria established by the design team with the assistance of E. O. Tofflemire and Associates, the enclosure wall consultant:

Seismic drift:

The curtain wall was to be constructed to allow for a plus or minus 3/4" drift or movement in any horizontal direction between floors, as follows:

- Normal to the plane of the curtain wall:
  plus 3/4" (in),
  minus 3/4" (out);
- Parallel to the plane of the curtain wall:
  3/4" to the right,
  3/4" to the left.

Horizontal force factor for elements of structures - 'C_p' (UBC Table 23-J):

- Exterior Wall, C_p= 0.20 normal to flat surface,
- Cantilever Wall, C_p= 1.00 normal to flat surface,
- Connection, C_p= 2.00 in any direction

Wind pressures:

- 0 to 30' = 15 psf,
- 30 to 50' = 20 psf,
- 50 to 100' = 25 psf.

Deflections:

- The deflections of any metal framing member in a direction normal to the plane of the wall should not exceed 1/240 of its clear span or 3/4", whichever is less;
- The maximum deflection of any section in the plane of the glass should not exceed 1/8";
- The deflection of any horizontal member supporting glass, when carrying its full design dead load, should not exceed 1/360 of the clear span of the member or 1/8", whichever is less;
- The deflection of any member in a direction parallel to the plane of the wall, when carrying its full design load, should not exceed 75% of the design clearance dimension between the member and the top of the panel, sash, glass, etc.

Anchorage and support of curtain wall elements:

- Points of support for the curtain wall were to be braced in the three orthogonal directions to resist loads from any direction, including positive and negative wind pressures, seismic forces, etc.;
- Curtain wall elements and their applicable anchorage assemblies should be designed to accommodate thermal, seismic, and building movements without harmful effect to the curtain walls, including glass, glazing, and sealant.

Sealants:

- Sealants should be installed such that there is no adhesive or cohesive failure of joints.

Visual criteria:

As an extension of the design philosophy of the overall project, the architects set the following visual criteria:

- Because the building form is highly articulated, the enclosure wall should be relatively smooth and present a flush appearance;
- The wall should look like lightweight material, not like painted structural walls;
- The enclosure wall should honestly express the interruption of the space modules with the structural columns;
- Panels should look continuous with only a subtle indication of joints to express the means of fabrication, and without demarcations or shadows which would disjoint the wall into conspicuously separate pieces.

DETAILED DESIGN OF THE ENCLOSURE WALL

The architects and E. O. Tofflemire and Associates designed the wall as an Uncoupled Element based upon the design criteria previously outlined. The lightweight enclosure system developed in the wall's conceptual design stages was initially composed of steel mullions supporting porcelain enamel steel panels and glass panels.

As the design evolved, the steel panels were changed to aluminum. The weight of the enclosure system, averaging glass, aluminum panels, the mullion system, and other miscellaneous materials, was about 4.3 pounds per square foot, making the system relatively lightweight and therefore an Uncoupled Element as previsouly assumed.

The combination of flush and smooth glass and metal surfaces was consistent with the design concept . . . of a "skin" only, an Uncoupled Element.

The curtain wall design incorporated separate glass and aluminum panels anchored to the mullion system, which was, in turn, anchored to the Dynamic Structure. Support mullions were located 5'-0" on center, glass panels were 5' x 5', and aluminum panels 5' x 9'. Glass panels were 1/4" thick, and aluminum panels were 3/16" thick. Because of the visual criterion of a smooth-appearing wall, the glass panels were detailed to be as nearly flush with the aluminum panels as possible. This detail was accomplished by the use of 1/4" thick perimeter butt glazed glass panels with no exterior stops. This type of glass installation was feasible because the glass panels were of relatively small size. In some areas of the complex, such as the cafeteria area and interlinking corridors between adjacent cruciform buildings, the larger size of the glass panels necessitated a different glazing system which used stops. In addition to the flush detailing of the windows, the aluminum panels were designed with smooth natural finishes, and joints between panels were designed as subtle reveals to express the means of fabrication, while still maintaining the continuous look of the wall surface. Furthermore, the combination of flush and smooth glass and metal surfaces was visually consistent with the design concept of the enclosure system as a "skin" only, an Uncoupled Element, rather than a coupled or "structural" one. Stiffeners were added to maintain panel flatness within 1/8" out of plane in 5'-0". To maintain the integrity of the lightweight enclosure system at the third and fourth floor interlinking corridors, one inch movement tolerance joints were provided at either end of each corridor's enclosure wall. Finally, for the most severe seismic conditions, the design had to take into account the interaction between the two perpendicular walls at typical corner situations. To avoid the possibility of potentially high amounts of stress at the corners, special 45° corner panels were designed to disengage from the support mullion system under severe loadings, allowing room for movement of the remainder of the cladding system, thus preventing extensive damage. A typical horizontal section of the wall at the 45° corner panels is shown in Figure 3-12.

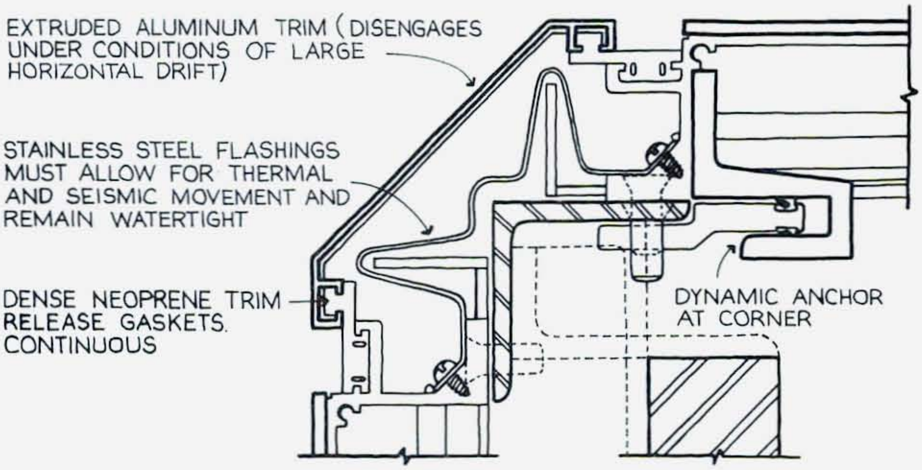


FIGURE 3-12. HORIZONTAL SECTION OF TYPICAL 45° CORNER PANELS.

By the time the design of the enclosure wall was completed and ready for bids, the materials systems chosen to meet the functional, structural, and aesthethic design criteria were the following:

Exterior cladding: Anodized aluminum sheet with clear or special color coatings.

Exposed and internal curtain wall sections: Anodized aluminum extrusions.

Flashings: Aluminum or stainless steel, as required, with mill finish.

Anchors and related structural components: Anodized aluminum extrusions, or steel with protective paint coating, as required.

Sealants:

- For glass to metal butt glazed joints: Silicone sealant compounded for an acetic acid cure.
- Secondary glass to metal and metal to metal: Silicone sealant.
- Exposed metal to metal, perimeter metal to concrete: Two part polysulfide base sealant.
- Concealed metal to metal and metal to concrete: Non-drying, non-skinning synthetic butyl rubber sealant.
- Joint fillers and back-up materials: Selected in accordance with written recommendations from the applicable sealant manufacturers for each specific application. Factors considered included shape, size, hardness, compatibility and bond breaking requirements.

SUBCONTRACTOR'S FINAL DESIGN AND DETAILING

The design of the curtain wall illustrated in the contract documents was carried out in a manner consistent with the requirements for an Uncoupled Element. The next step was the selection of a subcontractor who could manufacture and install the wall at an economical price, and yet satisfy the given objectives and requirements. The subcontractor was offered the option of modifying or adding details, subject to the architect's approval, as long as the visual and performance requirements were fulfilled.

Five companies with the capability of fabricating and installing this type of curtain wall system submitted bids. The Cupples Products Division of the H.H. Robertson Company was low bidder with a proposal based upon MBT-approved modifications and thus was awarded the subcontract.

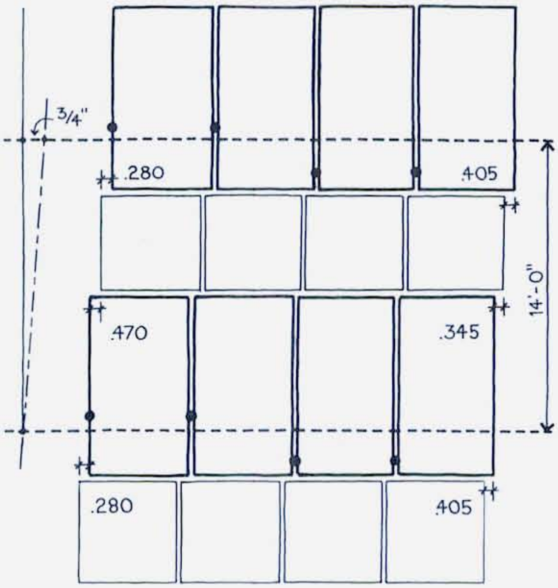


FIGURE 3-13. ELEVATION SHOWING LOCATION OF CURTAIN WALL CONNECTIONS AS DESIGNED BY SUBCONTRACTOR.

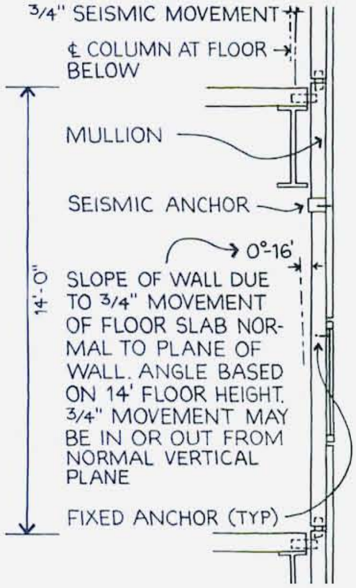


FIGURE 3-14. SECTION SHOWING SAME AS FIGURE 3-13.

Cupples Products' design group proposed changes in detailing, fabrications, and installation, but not in the concept of the curtain wall. Substantial modifications were made to the anchoring system to make the wall more efficient. The design modifications proposed in the shop drawings changed the location of the seismic anchors as shown in Figures 3-13 and 3-14. The final design still allowed 3/4" movement in and out from the plane of the wall, as well as 3/4" in either direction in the plane of the wall.

BUILDING AND TESTING OF A MOCK-UP UNIT OF THE CURTAIN WALL

Construction and installation of the test unit were performed as they would be at the actual site.

The architect's contract documents required that, upon approval of the shop drawings, the subcontractor build a full-scale mock-up of a section of the curtain wall in order to test its ability to meet the seismic and other design criteria that had been established. A full-size test unit provided a means of conducting both a visual evaluation and a performance testing of the wall. Construction and installation of the test unit were performed in the manner proposed for the completed structure and included all components, such as glass, sealants, anchor assemblies, and so forth. The structural steel frame, to which the curtain wall test unit was anchored, also simulated the actual structural frame to be constructed.

Visual review and approval was based on the quality standards outlined in the performance specification and included finish match and uniformity, joinery, tolerances, seals, flatness in smooth-faced surfaces, and so forth. Acceptable performance required approval of both the testing procedures and the resulting data submitted in a certified report.

The curtain wall mock-up unit was tested by the A. A. Sakhnovsky Construction Research Laboratory at Cupples Products' facilities in St. Louis, Missouri. The test procedures were in accordance with the testing methods and procedures described in the National Association of Architectural Metal Manufacturers (NAAMM) Standard TM-1-68T, "Methods of Test for Metal Curtain Wall." A test chamber was constructed on the interior side of the test wall with observation ports permitting examination of the interior surfaces and joints of the test assembly during the actual test periods. The interior of the air chamber was maintained at a uniform temperature of 70° F. with a relative humidity of 40%; the air pressure was varied as required for the test procedures.

The test unit consisted of a group of four aluminum frame curtain wall elevations (A,B,C, and D) constructed in the relative configurations which they would assume in the actual building complex (Figure 3-15). The mock-up was two full stories plus one spandrel plus the coping in height. Elevations A and B consisted of a vertical tubular mullion system with applied 1/8" thick aluminum spandrel panels plus separate "floating" glazing frames for single 1/4" thick perimeter butt-glazed lights; no exterior stops were utilized. Elevation C consisted of a similar mullion and panel system, but incorporated separate "floating" glazing frames for pairs of 1/4" thick exterior glass flush glazed into a tubular rail. Elevation D was a narrow vertical strip consisting only of aluminum panels. The wall also incorporated a full-height neoprene flashing at each 135° inside corner. The overall size of the test unit was approximately 45 feet wide by 35 feet high.

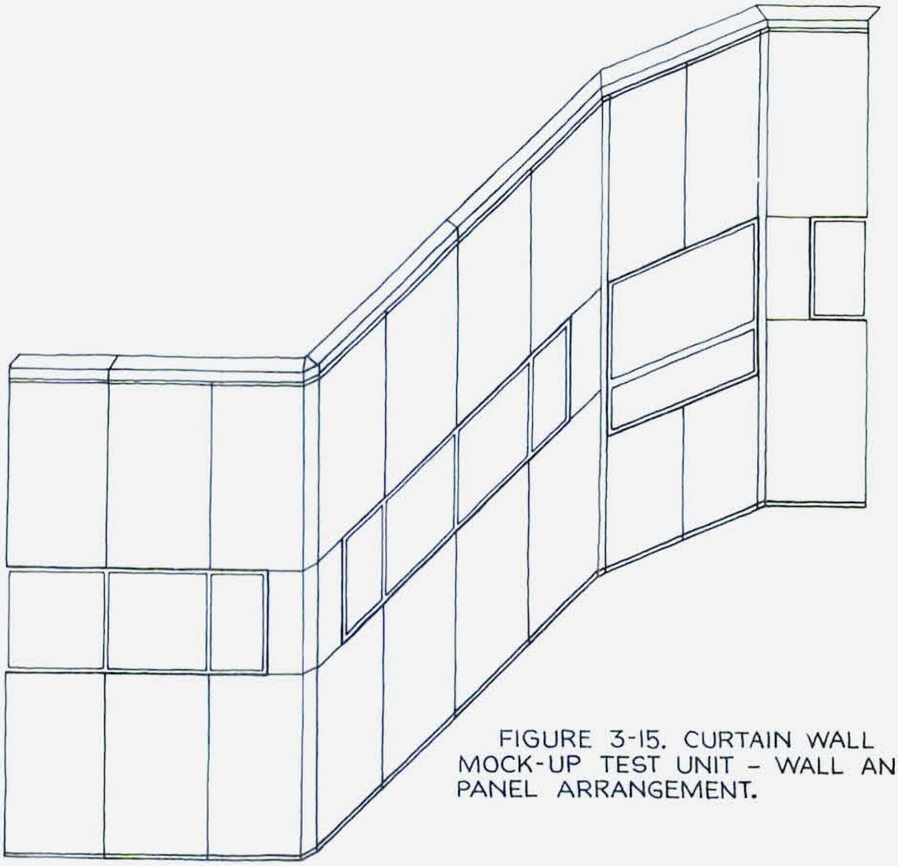


FIGURE 3-15. CURTAIN WALL MOCK-UP TEST UNIT - WALL AND PANEL ARRANGEMENT.

The mock-up unit was tested for static pressure air and water infiltration, dynamic pressure water infiltration, and static pressure structural performance. Static racking tests to simulate seismic movement were then conducted and the preceding tests repeated. Performance requirements, the tests applied to ascertain the wall's ability to meet those requirements, and the results of these tests are presented below. The tests appear in the order in which they were conducted.

Air infiltration by static pressure:

- Test applied: Static air pressure of 1.56 psf, equivalent to a 25 mph wind.
- Design criteria: Less than 0.06 cfm per square foot or 97.4 cfm total allowed.
- Performance results: The test wall was found to be acceptable, since only 0.05 cfm per square foot or 88 cfm total, including test chamber air leakage, which could not be segregated because of weather conditions, permeated the assembly.

Water infiltration by static pressure:

- Test applied: The wall was subjected to a water spray at the rate of five gallons per hour per square foot with static pressure of five psf for 15 minutes, equivalent to 20% of the positive pressure design load; and six pressure cycles of 2.5 minute duration imposing 3.9 psf and 10 psf loads, equal to 39 mph and 63 mph winds.
- Design criteria: There was to be no water infiltration.
- Performance results: No uncontrolled water leakage occurred in any of the tests, but several drops of water entered at one weep drain tube fitting at the "C" elevation.

Structural performance tests by static pressure using full design loads:

- Test applied: The wall was subjected to ± 25 psf (positive and negative pressure design loads) to measure deflection. It should be noted that 25 psf was the design load applied to the upper 8'-6" of level 4 and 20 psf was applied to lower portion of the mock-up unit. Deflections measured at the 25 psf design loads are shown below.
- Design criteria: No glass breakage or evidence of any other damange.
- Performance results:

	Allowable: 1/240 or .750"	Performance Results	
Elevation B:		+ 25 psf	- 25 psf
Outside corner mullion	.750"	.003"	.032"
Typical Mullion-level 3	.750	.454	.540
Typical Mullion-level 4	.750	.444	.545
Panel stiffener-level 3	.239	.122	.100
Vision sill	.239	.108	.181
Vision head	.239	.080	.156
Vision glass	-	.580	-

	Allowable: L/240 or .750"	Performance Results	
Elevation C:		+ 25 psf	- 25 psf
Vertical panel mullion	.323"	.012"	.030"
Vision glass	1.10	-	-

- There was no evidence of any damange or harm. Apparent excessive deflection was experienced at the vision head and at the horizontal muntin at the "C" elevation, but these included undetermined end movement which was to be measured in subsequent testing.

Seismic performance test:

- Test applied: The structural steel representing the floor at level 4 was designed so that it could be moved by means of screw jacks with respect to the floors at levels 3 and 5 (which remained fixed) to simulate seismic movement. The floor at level 4 was moved as follows:

  Inward (+) 3/4" normal to Elevation A; return to original position;
  Outward (-) 3/4" normal to Elevation A; return to original position;
  Inward (+) 3/4" normal to Elevation C (45° to Elevations A and B; return to original position;
  Outward (-) 3/4" normal to Elevation C (45° to Elevations A and B; return to original position.

- Design criteria: as stated earlier in this chapter.

- Performance results:

  Elevation A: Movement normal to the elevation produced no effect on the "A" wall. Movement at 45° caused displacement of the glazing sill closures with respect to the frame sills by 1/8". This figure was low becuase some of the 3/4" movement in the floor resulted in bending of the structure rather than movement at the test wall.

  Elevation B: Tests normal and at 45° to this elevation resulted in displacements of the glazing sill closures of 1/4" to 5/16" with respect to the glazing frame sills. When the floor was returned to its original position, some sills failed to return to their original positions by 1/16" to 1/8" due to friction or drag on neoprene weatherstripping and other wall components.

  Elevation C: No effects were noted in Elevation C.

Water infiltration by Dynamic Pressure:

- Test applied: The wall was subjected to water spray at the rate of five gallons per hour per square foot and winds from an 1800 horsepower aircraft engine wind generator at nominal 5 psf (20% of 25 psf design load) for 15 minutes.

- Design criteria: No uncontrolled water infiltration.

- Performance results: No water appeared on the interior of the wall.

Water infiltration by Static pressure (supplementary test):

- Test applied: The wall was subjected to a water spray at the rate of five gallons per hour per square foot and static pressure of 5 psf for 15 minutes, cycled pressure for 12 minutes, 10 psf for 10 minutes, and 15 psf for 10 minutes.

- Design criteria: No uncontrolled water infiltration.

- Performance results:

  There were no leaks during the 5 psf and cycled pressure tests.

At 10 psf loading after three minutes, a leak at the rate rate of one drop/second occurred between the top of the lower glazing frame and the head trim; total leakage was about one ounce.

At 15 psf, water leakage developed at the outside corner as a result of air and water percolation at the stacked joint at the bottom of the uppermost panels. Uncontrolled percolation occurred at the level 4 exposed corner panel weeps, with water surging periodically over the sill.

Structural performance tests by static pressure:

- Test applied: The wall was subjected to the following structural loading held for ten seconds each:

  For the lower 6' of level 4 and below:
  ± 20 psf (design load) and
  ± 30 psf (1.5 x design load);

  For the top 8'-6" of the mock-up:
  ± 37.5 psf (1.5 x design load)

- Design criteria and performance results:

Design criteria	Performance Results	
(L/240)	+ 20 psf	- 20 psf
.421"	.308"	.296"
.421	.207	.277
.421	.325	.310

- There was no damage or harm experienced as a result of the above tests.

Test to Failure:

Negative pressure was slowly increased from 30 psf in 10 psf increments. At -58 psf the spandrel panel frame welds at the first typical mullion in Elevation A just below the vision glass failed. This failure was accompanied by release of the adjoining glazing frames and glass failure on each side of the mullion.

Inward (+) 3/4" normal to Elevation A; return to original position;

Outward (-) 3/4" normal to Elevation A; return to original position;

Inward (+) 3/4" normal to Elevation C (45° to Elevations A and B); return to original position;

Outward (-) 3/4" normal to Elevation C (45° to Elevations A and B); return to original position.

Overall Test Results

The wall was tested in accordance with and met the architect's design criteria for static pressure air and water infiltration, static pressure structural performance and seismic racking, except that some excessive movements occurred as described in the static pressure structural test. The wall was also satisfactorily tested for dynamic pressure water infiltration.

INSTALLATION OF THE CURTAIN WALL AT THE SITE

Proper installation was necessary to ensure the wall's performance as an Uncoupled Element.

In any system designed to have a certain configuration, weight, stiffness, and connectivity, there is always the danger that the field installation may alter these characteristics to the extent that it does not perform as intended. In the case of the curtain wall, the decision that it should be an Uncoupled Element was the critical factor which would determine the wall's response during an earthquake. Should improper installation change the connectivity to the degree that all or a portion of the wall would act instead as a Coupled Element, then there would be the probability of excessive damage to the wall during a severe earthquake. Thus, good design in itself was not sufficient: the installation had to be consistent with the basic performance objectives and design criteria for the wall. For example, the design team intended that the subframe be anchored with pin connections to permit rotation, and that the 45° corner panels be installed to permit disengagement upon heavy seismic impact. Had a few extra screws or welds been added in the wrong locations to make the installation "stronger," the entire concept of the wall being lightweight and able to move in response to seismic loads would be changed. Originally, the design team thought that one would be able to pull off the 45° corner panels by hand. However, the installation resulted in panels which will disengage during an earthquake, but cannot be easily pulled off by hand. The design team's experience with the curtain wall emphasized the importance of recognizing potential changes in concepts which may occur as a result of installation; design teams must apply the necessary field inspection and testing procedures to insure that the design concept is fully carried out throughout the entire building process.

SUMMARY

The design and construction of the curtain wall system of the IBM complex is an example of the impact of the theory of the Dynamic Model on building design. The curtain wall, designed as an Uncoupled Element, was affected by even the earliest decisions in the design process. The site analysis, which noted the geological difficulties of the site, including a fault, determined the period of the site to be relatively short. This fact, in combination with an initially anticipated building period in a similar range, meant that in order to avoid a condition of resonance, the engineers had to design the building such that its period would be lengthened. Hence, the final design utilized a ductile steel moment resisting frame and was very flexible with a period of 1.0 seconds. The direct impact of this flexibility was an unusually large interstory drift of 3/4", making the design of an enclosure system especially challenging. The design team also determined that the enclosure system must be relatively lightweight, so that it would not increase the already high forces for which the building must be designed. The wall was designed, therefore, as an Uncoupled Element. The curtain wall design was unique in that its connections permitted a story to story displacement of 3/4" without significant damage, and the effectiveness of the design was confirmed by an extensive series of tests on a mock-up of the wall. Final detailing and installation successfully carried out the concept of the wall as an Uncoupled Element, thus completing the first design and construction of a building system following the concepts of the Dynamic Model.

Many people contributed to both the research effort and its design application, and special credit is due IBM for their interest in the most advanced design methods for earthquake safety.

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International Business Machines Corporation
Charles Barkis, Project Manager, San Jose
James Bonner, Manager of Design and Construction, New York

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David C. Boone and Alan R. Williams, Principals-in-Charge

Gerald M. McCue, Principal-in-Charge of Design Team

Consulting Structural Engineers:

Forell/Elsesser Engineers

Nicholas F. Forell, Principal-in-Charge

Consulting Mechanical Engineers:

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Duane Hanson, Principal-in-Charge

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Consultant on Enclosure Wall:

Eugene O. Tofflemire and Associates

General Contractor:

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Subcontractor for Enclosure Wall:

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Chapter Four

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Design of Ceiling Systems and Partitions for Their Dynamic Environments

"Architectural" components in buildings have normally been considered to be "nonstructural" and, as a result, less effort has been made to design them for seismic conditions than has been made for structural components. Recently a great deal of attention has been focused on environmental service systems, such as mechanical equipment, lighting fixtures, and so forth, and the result has been improved seismic criteria for these systems. Some local codes have attempted to minimize earthquake hazards to occupants of buildings from failures in architectural components; for example, some codes require specific kinds of ceiling bracing. Other codes merely require that all nonstructural components be designed for static horizontal loads. The

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Uniform Building Code (UBC), for example, requires that ceilings and partitions be designed to withstand lateral loads that are simply a percentage of their own weight (partitions also have deflection limits). However, all of these code provisions are attempts merely to approximate selected conditions that earthquakes may impose on building systems. The Dynamic Model, described in Chapter Two, provides a different approach to the design of architectural components from that previously established by the codes, because it considers all of the dynamic conditions that may exist. This chapter applies the concepts of the Dynamic Model to the analysis and design of components: a method is developed for analyzing the interaction of ceiling and partition systems; this method, in turn, makes possible the design of systems that are compatible with their Dynamic Environments. Although this approach has not been tested and must, therefore, be considered theoretical at this point, the hope is that it will eventually enable architects to design components to withstand seismic motions with considerably less damage than is possible with present methods.

The Dynamic Model provides a different approach to the design of architectural components from that previously established by codes, because it considers all of the dynamic conditions that may exist.

Limitations of Existing Methods of Designing Components for Earthquakes

While for relatively stiff or relatively small structures the use of criteria for component design established by the UBC and/or some local codes may be adequate, for relatively flexible or for multistory structures these criteria may not be adequate. The UBC requires lateral restraint for a constant %g of the component; this requirement does not consider the dynamic effects of earthquakes. Earthquakes will often subject connected or adjacent components or systems to input motions that conflict with each other. For example, a partition may be moving in one direction while the attached ceiling is moving in the opposite direction, a situation likely to result in damage.

Earthquakes will often subject connected or adjacent components or systems to input motions that conflict with each other.

Recent modifications to some building codes require that suspended ceiling systems be rigidly braced to the upper floor or roof so that they will follow not only the horizontal motions of the upper floor, but also the vertical motions. This requirement recognizes that uplift motions may result if the vertical suspension system is not rigidly braced, but does not recognize that other problems can be created as a result of the bracing. For example, in flexible structures, heavy, rigidly braced systems may in some cases collide with the Dynamic Structure, causing damage to one or both systems. Rigidly braced ceiling systems connected to typical partition systems may be damaged at their interface. If the potential for such damage is reduced by the provision of excessive gaps between the systems, fire or acoustical separations may be difficult to achieve.

An Alternative Approach to Component Design Utilizing the Dynamic Model

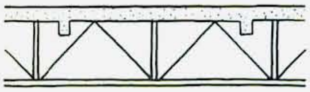
The Dynamic Model presents an alternative method of analyzing and designing for building response under seismic conditions. This method entails new responsibility for the architect: components can no longer be considered as isolated entities, nor can the overly simplified concept of resisting a constant lateral load suffice. Instead, building components and systems must be considered in their Dynamic Environments, composed of multidirectional motions of varying frequencies and accelerations. Such a broadened context for the design of components and systems may appear to be too complex to be practical. However, this study proposes that if designers thoroughly understand the motions of buildings and their individual components or systems, they will be better prepared to design systems that are less susceptible to damage during earthquakes. Furthermore, a logical and practical method of achieving such a goal can be developed, and this study presents one such possible method.

Conclusions Based Upon the Study of Component Interaction According to the Dynamic Model

The following sections of this chapter develop an approach for analyzing the interaction of components according to the principles of the Dynamic Model. An intuitive approach was used to predict the likely motions of the systems studied, and then to suggest means of accommodating such motions. Many assumptions have been made in the formulation of the approach because test data is not presently available that would either support or refute the method used. Although the analysis focuses on ceiling and partition systems, the same methods could be employed in the analysis of elevator shafts, stair wells, exterior enclosure systems, mechanical, electrical, and plumbing systems, and so forth.

The analysis of ceiling and partition systems resulted in a number of general conclusions regarding the interaction of building components. The hope is that these conclusions will not be accepted without challenge, but that they will encourage a more creative approach to the design of all building systems, one which considers each component in the context of its Dynamic Environment.

- In relatively stiff buildings with interstory relative displacements of less than about ± 1/4 inch, ceilings and partitions should be rigidly braced to the supporting structure, including compression bracing to the structure above for suspended ceilings.
- For relatively flexible buildings the only general statement that can be made is that a system must be selected, designed, and connected so that its response is compatible with its Dynamic Environment.
- The present Uniform Building Code's criteria for seismic design of ceiling and partition systems are inadequate because the criteria consider only lateral loads, and then as if they were constant. An exception is conventional wood frame construction, which has an inherent resiliency that makes it less susceptible to extreme displacements at any one location.



S.F CODE (SYMBOLIC)

- Local building codes, such as the San Francisco code, which requires that all suspended ceiling systems be vertically braced to the upper floor with compression members, as well as diagonally braced, do not recognize the ceiling's dynamic interaction with other systems that either are not or can not be similarly braced. Although this prescriptive bracing requirement is probably the correct approach for design of components in relatively stiff structures, in more flexible structures there may be alternatives that produce a more compatible relationship with other systems and result in less damage.

ARCHITECTURAL DESIGN OF BUILDING COMPONENTS AND SYSTEMS

Motions of the ground induce response motions in a building and all of the building's components contribute in varying degrees to the nature of the response, as described by the roles of the Dynamic Model: the Dynamic Structure, Coupled Elements, and Uncoupled Elements. Building response is not uniform throughout: some floors or wings of buildings will exhibit different responses than others. Although all components may directly interact and contribute to the overall building response, for component design, one need consider only building response at the component's location, its "Dynamic Environment." For the design of a particular component one may isolate the motions that will occur at its location and analyze it with respect to those components with which it may interact. Two components are assumed to directly interact if they are in contact or are capable of coming in contact. Thus, a component or a connection between components need only be designed for the direct influence that other components may have on that component's motions during an earthquake.

"component" vs. "system"

For design purposes a distinction must be made between a "component" and a "system" of components. In this chapter the word "component" will refer to the individual pieces that comprise a "system." For example, a partition system may be composed of gypsum board panels, metal studs, and so forth. Each panel and each stud is a component of the partition system. For a ceiling, each T-bar section, each lay-in tile, and so forth, is a component of the ceiling system.

interface

The point at which adjacent systems that are in contact or are capable of coming in contact with each other is called the interface between the systems. Knowing the potential influence of one system's motions on another system, one can then determine if the systems are capable of accommodating these influences without damage, either by means of their interface condition or by their own inherent physical properties. If so, then the systems are said to be "compatible." The factors that can be controlled by the designer in order to control the influence of one component on another component are further described below.

compatible systems

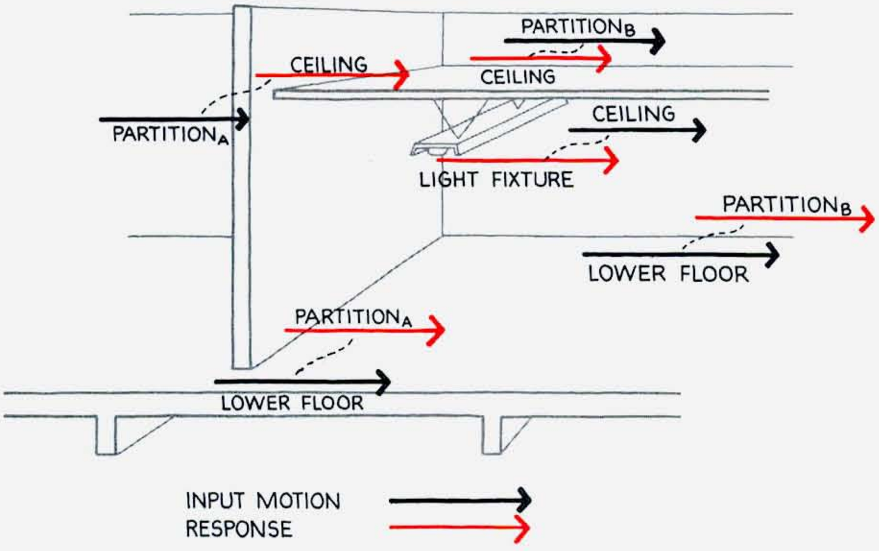


FIGURE 4-1. HIERARCHY OF INTERACTION.

Types of Interaction Between Systems

"Dominant/subordinate" and "mutual" are the two types of interaction between components that were defined in Chapter Two. In the first category, one component significantly influences the response of the second component, while the second component has little influence on the first. The second category describes interaction of two components where each one has a significant influence on the response of the other one. A particular system, analyzed in its Dynamic Environment, may be adjacent or connected to more than one system. In its Dynamic Environment it may have a dominant relationship with one system, a subordinate relationship with another system, and be mutually interactive with a third system. In any case, in a given Dynamic Environment there will exist a hierarchy of interaction. For example, the structural floor slab may dominate a partition system attached to it, the partition may, in turn, dominate a ceiling system, and the ceiling system may, in turn, dominate the lighting fixture suspended from it (Figure 4-1). In this case the ceiling system is subordinate to the partition system, but it dominates the response of the lighting fixture.

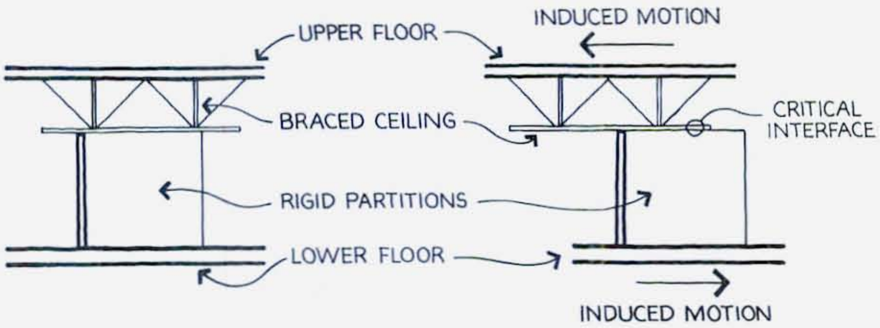


FIGURE 4-2. EXAMPLE SHOWING IMPORTANCE OF DESIGNING AN INTERFACE TO PRODUCE COMPATIBLE RESPONSES OF TWO SYSTEMS.

Figure 4-2 is an example of the importance of making two systems compatible. The ceiling system is braced and suspended from the upper floor and will be dominated by the upper floor. A rigid partition system is cantilevered from the lower floor and will be dominated by the lower floor. The two systems are located in a relatively flexible building, which will have significant interstory relative displacement. Because of the rigidity of the two ceiling and partition systems, the interstory relative displacement must be accommodated at the interface between the two systems. The two systems either could be totally separated, or, as will be discussed later, a connection could be designed that would make their conflicting motions compatible.

Two systems will be compatible if their interface conditions permit them to respond to the input motions of their Dynamic Environments without damaging each other.

Two systems will be compatible if their interface conditions permit them to respond to the input motions of their Dynamic Environments without damaging each other. Figure 4-3 represents a situation in which the physical properties of the two systems and the input motions of their Dynamic Environments are such that they can be rigidly connected to each other and respond in unison without damage. For the hypothetical partition and floor shown, the assumption is that there are no other input motions to the partition that would cause it to respond differently from the way it would due to its rigid con-

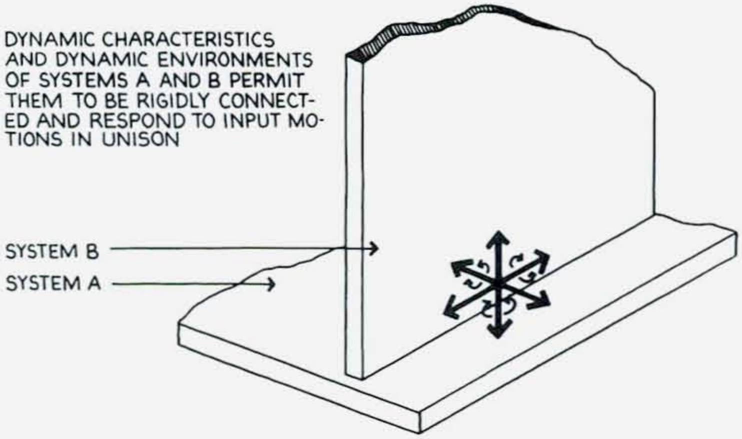


FIGURE 4-3. COMPATIBLE RESPONSE OF TWO SYSTEMS RIGIDLY CONNECTED. MOTIONS OF A AND B ARE SIMILAR.

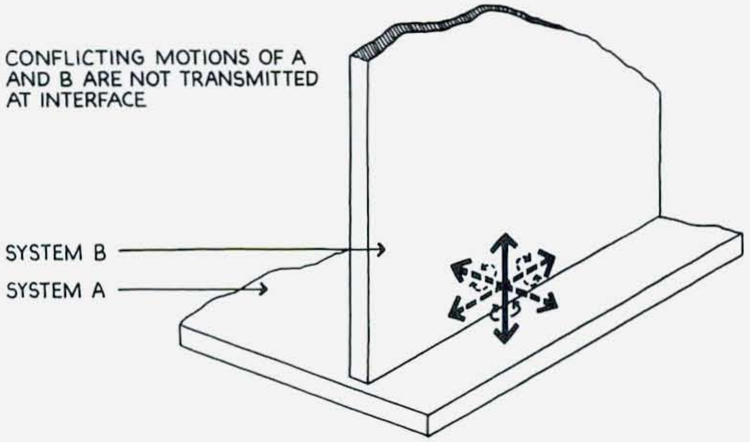


FIGURE 4-4. DESIGNING THE INTERFACE BETWEEN TWO SYSTEMS TO TRANSMIT ONLY MOTIONS THAT ARE COMPATIBLE.

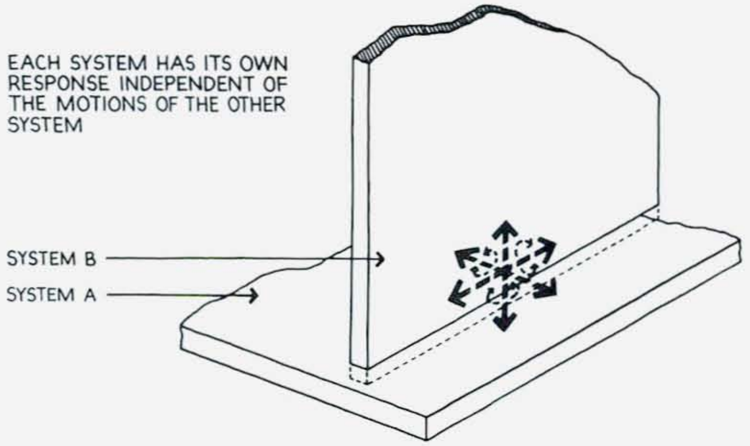


FIGURE 4-5. SEPARATING TWO SYSTEMS SO THAT THEIR RESPONSES ARE INDEPENDENT.

nection to the floor. Figure 4-4 illustrates how the connection at the interface between two systems can be designed to transmit only those motions of the one system that are compatible with the motions of the other system, and vice versa. Thus, the assumption is that in certain directions the one system will respond differently from the other because of either significant differences in their physical properties or the conflicting motions imposed upon it by other systems. In this case the connection at the interface must accommodate the difference in responses, or damage will occur. In some instances, neither of the first two methods will result in the compatible response of two systems. Then one must design the systems to be separate so that each system will have its own response independent of the motions of the other system (Figure 4-5).

The Effect of Physical Properties on the Interaction Between Systems

The physical properties of two components and their interface conditions determine whether the relationship between them will be one of "dominant/subordinate" interaction or "mutual" interaction. Physical properties determine, in part, a system's dynamic characteristics and the potential type of interaction that system may experience relative to other systems, as described below:

- mass: all other factors being equal, a more massive system will, in general, tend to dominate a less massive system; systems of similar mass will tend to be mutually interactive.
- stiffness: all other factors being equal, a stiffer system will, in general, tend to dominate a less stiff system; systems of similar stiffness will tend to be mutually interactive.
- configuration: all other factors being equal, the geometry of the system may determine its ability to be dominant, subordinate, or mutually interactive with another system.

In addition to affecting the degree of interaction between systems, physical properties may affect a system's ability to undergo, with little or no damage, horizontal shear forces; overturning moments; distortions of geometry, particularly those due to interstory relative displacements; and interaction with systems whose responses are out-of-phase with the given system. For instance, a heavy component will be likely to be subjected to greater forces due to acceleration, a flexible system will be capable of displacing greater distances than a stiff system, and a component that is tall and slender will be more likely to overturn than a shorter component. The ability of any system or component to undergo the forces and displacements described above will also depend upon its interfaces with other systems, as described in the next section.

The Effect of Interface Conditions on the Interaction Between Systems

Designers must solve the conflict between the need to anchor adjacent systems to sustain shear forces and overturning moments, and the need to allow for the dissimilar responses of the systems in terms of relative displacement and vibrational effects.

When two or more systems are rigidly connected or tightly abutt ... the stiffest system will attempt to support the more flexible ones, and may fail in its effort to do so.

Physical properties determine a system's inherent tendency toward dominant, subordinate, or mutual interaction, but the type of interface the component has with another system also affects the system's dynamic characteristics and can alter its degree of interaction with another system. Designers can often control the physical properties of a system by means of material choices and design of the system's configuration; in addition, they may also be able to design the interface between two systems to encourage a particular system to be dominant, subordinate, or mutually interactive with another system. When designing two systems that will be adjacent or connected, designers must solve the conflict between the need to anchor the systems to sustain shear forces and overturning moments, and the need to allow for the dissimilar responses of the two systems in terms of their relative displacement and vibrational effects. Too often designers misunderstand the consequences of joining together two components, particularly when the components have different relative stiffnesses. When two or more systems are rigidly connected or tightly abutt each other, they are no longer free to deflect according to their own dynamic characteristics. The stiffest component will attempt to support the more flexible components connected to it, and may fail in its effort to do so. Hence, the design of the connections at the interface of two systems is critical to designing systems with compatible responses. An understanding of the various directions and types of motions that adjacent systems can transmit to each other makes possible the design of interfaces that transmit only those motions that can be accommodated with little or no damage by each system. Interfaces are of two basic types:

connected interfaces

- Connected interfaces: For dominant/subordinate interaction, some or all of the dominant system's motions are transmitted to the subordinate system. For mutual interaction, some or all of one system's motions are transmitted to the second system, and vice versa.

unconnected interfaces

- Unconnected interfaces: No one system's motions are transmitted to the second system, and vice versa.

DESIGNING CEILING AND PARTITION SYSTEMS FOR THEIR DYNAMIC ENVIRONMENTS

The remainder of this chapter deals with specific aspects of the Dynamic Environments for ceiling and partition systems. Generic types of systems will be analyzed to determine their physical properties, and then their interface with other systems will be studied in order to determine the requirements for designing compatible groups of systems for their Dynamic Environments. The physical properties distinguishing each generic type of ceiling and partition system are presented first. These properties give the systems the inherent ability to endure certain input motions. Next the interface conditions between systems are analyzed to determine the potential for interaction between different systems depending on the design of the interface between them. The analysis of physical properties and interface conditions is then applied to a specific example of an integrated system of ceiling and partition systems.

The following sections analyze the relative displacement effects on ceiling and partition systems when they act as Uncoupled Elements, which is the most frequent condition occurring in buildings. In some cases when systems have physical properties and interface conditions that make them act as Coupled Elements, the architect must collaborate more closely with the structural engineer, because such systems must be included in the structural analysis of the building. Once the structural engineers determine the vibrational effects and interstory relative displacements of the Dynamic Structure for different locations in the building, the architects are then able to proceed with the task of designing the systems to accommodate those characteristics of the Dynamic Environment. The general procedure for calculating the forces acting on components caused by vibrational effects has been discussed in previous chapters of this study. In addition to the relative displacements between the Dynamic Structure and each system, relative displacements between systems must also be accommodated. This chapter studies relative displacement effects that may occur in buildings with relatively flexible responses, that is, buildings whose interstory relative displacements are greater than about ± 1/4 inch. Systems that are subjected to less than ± 1/4" displacement can normally be designed according to the latest codes and design procedures for bracing systems in buildings.

This chapter studies relative displacement effects that may occur in buildings with relatively flexible responses.

PHYSICAL PROPERTIES OF CEILING AND PARTITION SYSTEMS

When ceiling and partition systems are subjected to accelerations and displacements that exceed those that the system's physical properties can accommodate, damage will occur. In many cases, however, interacting systems can be designed so that selected input motions are transmitted to those systems that have the capability of accommodating these motions with little or no damage. Thus, an understanding of the physical properties of the systems of a building, and hence their dynamic characteristics (accelerations, displacements, and frequencies of vibration) will allow architects to determine the direction, type, and extent of motions that various systems can accommodate. In this section idealized types of ceiling and partition systems are identified. Then seismic design criteria are developed for each type of system; if damage is to be mitigated, the appropriate criteria must be met whenever one system interacts with another.

CEILING SYSTEMS

This study of ceiling systems will consider the "suspended" variety only. The scope of the study is thus sufficiently limited to permit a thorough and reasonably simplified analysis to be made of ceiling systems. The choice of the suspended ceiling is appropriate because this type of system constitutes a sizable share of the total ceiling installations made in commercial buildings, and such systems are typically installed in multistory buildings. Several variables define the different types of suspended ceiling systems; all suspended ceilings, however, share some important characteristics. With respect to the Dynamic Structure:

- All ceiling systems in this study are Uncoupled Elements.
- All systems are suspended from the underside of the floor or roof above (hereafter simply called the "upper floor"), which is part of the Dynamic Structure, and they are suspended by some type of tension supports at frequent intervals.
- Because the ceiling is always assumed to be connected to the upper floor, a part of the Dynamic Structure, it will always be subjected to motions induced by the upper floor.
- Any effort to restrain the ceiling so that it cannot respond to the motions of the upper floor will result in damage to some part of the ceiling system or its connection to the upper floor.

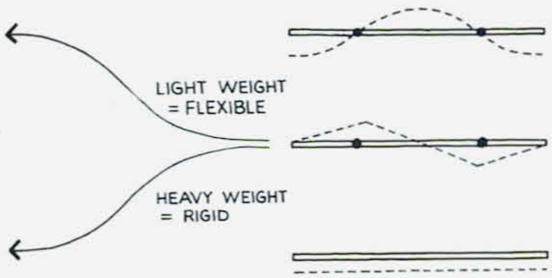
With respect to the systems' own physical properties:

- All suspended ceilings can be thought of as a horizontal surface, whether they appear as a flat plane, or as a series of coffers within a grid.
- The mass of the ceiling system is assumed to be equal to the mass of the ceiling plane materials; the mass of the tension supports is considered insignificant.

The following sections will analyze the effect of the physical properties of ceiling systems on their response to input motions. The analysis will begin with the ceiling's subsystems, analyzed in two dimensions, combine these subsystems to produce the basic ceiling types in two dimensions, and finally combine ceiling types to produce the basic

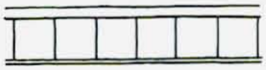
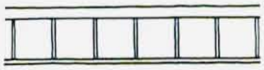
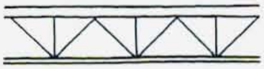
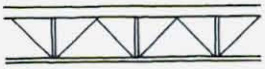
DESCRIPTION | DIAGRAM | COMMENTS

CEILING PLANE SUB-SYSTEMS:



DESCRIPTION	COMMENTS
FLEXIBLE	CONNECTIONS ALLOW MOVEMENT; 1' × 1' TILES TYPICAL; FRAME FLEXIBLE
MODERATELY FLEXIBLE	CONNECTIONS ALLOW MOVEMENT; 2' × 4' PANELS TYPICAL; FRAME RIGID
RIGID	CONNECTIONS RIGID; GYP. BD. SHEETS, ETC., TYPICAL; FRAME RIGID

CEILING SUSPENSION SUB-SYSTEMS:

DESCRIPTION	DIAGRAM	DYNAMICALLY ACCEPTABLE	COMMENTS
UNBRACED FLEXIBLE		NO	NO COMPRESSION MEMBERS. SUBJECT TO "FLOATING" WHICH MAY CAUSE CHAOTIC BOUNCING RESULTING IN DAMAGE - THEREFORE ELIMINATED AS DYNAMICALLY ACCEPTABLE SUBSYSTEM
UNBRACED RIGID		YES	CARRIES FORCES IN TENSION AND COMPRESSION; NO "FLOATING"
BRACED FLEXIBLE		NO	SAME PROBLEMS AS UNBRACED FLEXIBLE SUSPENSION ELIMINATED AS DYNAMICALLY ACCEPTABLE SUBSYSTEM
BRACED RIGID		YES	CARRIES FORCES IN TENSION AND COMPRESSION; NO "FLOATING"

DYNAMICALLY ACCEPTABLE CEILING TYPES:

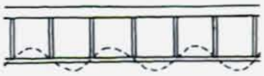
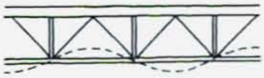
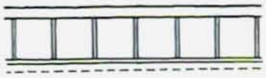
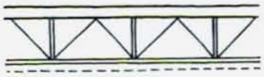
DESCRIPTION	DIAGRAM	COMMENTS
FLEXIBLE CEILING PLANE - UNBRACED SUSPENSION		= FLEXIBLE UNBRACED CEILING TYPE
FLEXIBLE CEILING PLANE - BRACED SUSPENSION		= FLEXIBLE BRACED CEILING TYPE (RESPONSE SIMILAR TO THAT OF RIGID CEILING PLANE - BRACED SUSPENSION
RIGID CEILING PLANE - UNBRACED SUSPENSION		= RIGID UNBRACED CEILING TYPE
RIGID CEILING PLANE - BRACED SUSPENSION		= RIGID BRACED CEILING TYPE RESPONSE SIMILAR TO THAT OF FLEXIBLE CEILING PLANE - BRACED SUSPENSION

FIGURE 4-6. CEILING SUBSYSTEMS AND CEILING TYPES.

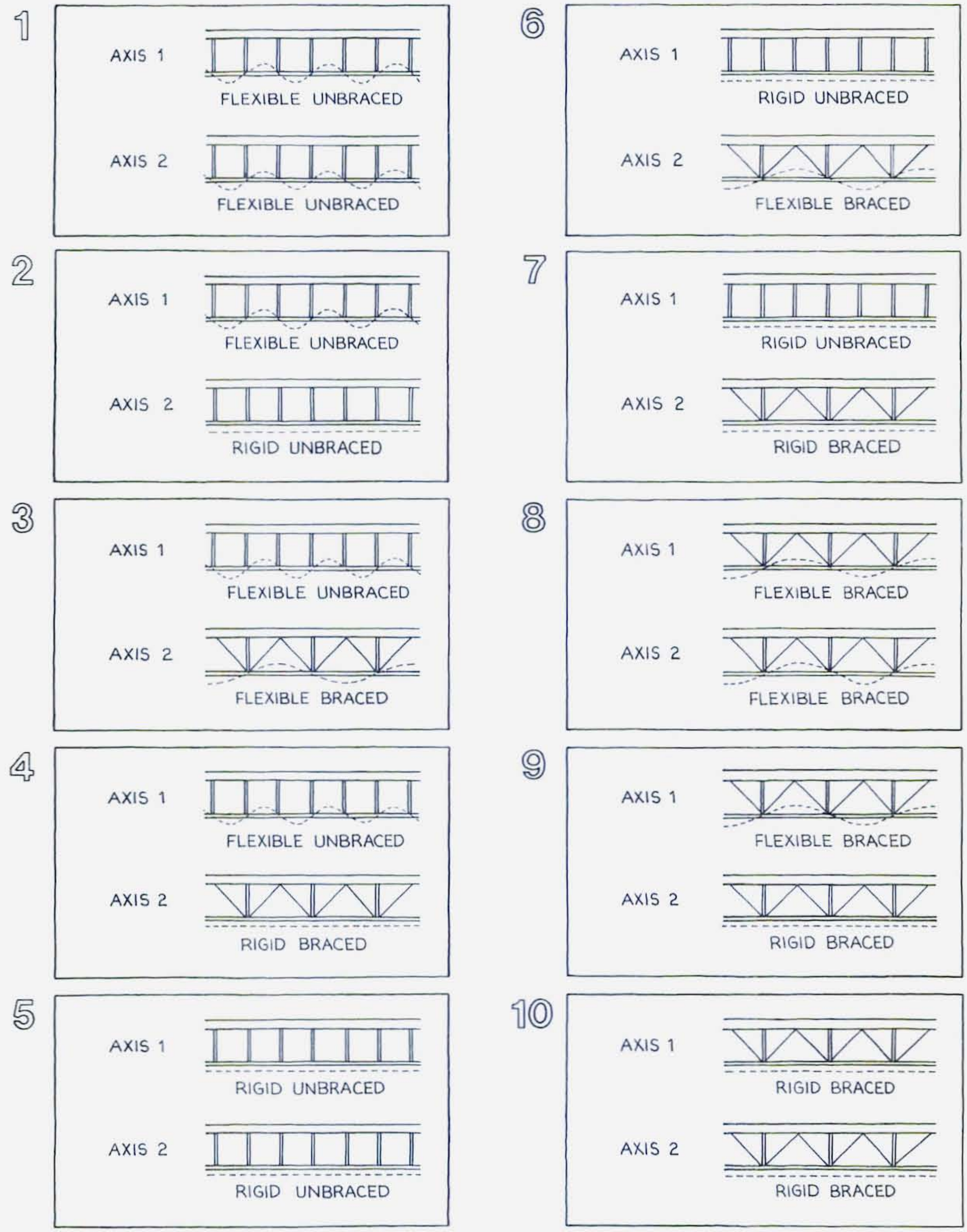


FIGURE 4-7. GENERIC SUSPENDED CEILING SYSTEMS. SYSTEMS ARE REPRESENTED BY CEILING TYPE IN EACH AXIS.

three-dimensional ceiling systems that can be designed to be dynamically compatible with other systems in a building with "flexible" response. Figures 4-6 and 4-7 present a summary of the ceiling subsystems (ceiling plane and ceiling suspension), ceiling system types (two-dimensional analysis), and generic ceiling systems (three-dimensional analysis), that are analyzed in the remainder of this section. The generic ceiling system discussion at the end of this section outlines the criteria for designing the different ceiling systems to undergo various input motions with little or no damage.

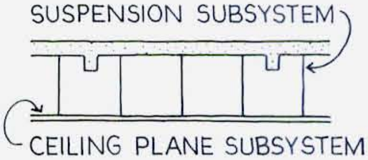
Ceiling Plane Subsystems

Ceiling plane subsystems consist of components such as T-bars, lay-in tiles, gypsum board, concealed splines, and so forth, that are combined to form the plane of the ceiling system. The ceiling plane's physical properties are based upon the physical properties -- mass, stiffness, and configuration -- of its individual components. The ceiling plane's physical properties that affect its response are described below.

Configuration. Because the ceiling plane has been defined to be a horizontal plane of some thickness, its configuration is considered to be a fixed variable in this study.

Mass. The mass of the ceiling plane constitutes the mass of the entire ceiling system, since the weight of the suspension system is minimal. The mass of the system is one of the factors that determines the extent of its accelerations and patterns of displacements.

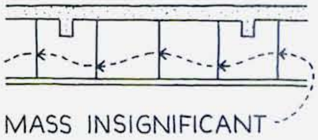
Stiffness (flexibility). Given the correct design criteria for displacement by the engineer, the architect must then be able to analyze a system for its potential to satisfy those criteria. The stiffness of the ceiling plane is the physical property that primarily determines the system's inherent ability to undergo input motions without damage. Configuration, stiffness, and mass all contribute to the ceiling plane's tendency to act in a flexible or stiff manner. Because the direction perpendicular to the plane of the ceiling is the weakest axis, this axis will allow some flexure of the system. The type of connections between the components and the stiffness of the individual components determine three potential deflection patterns:



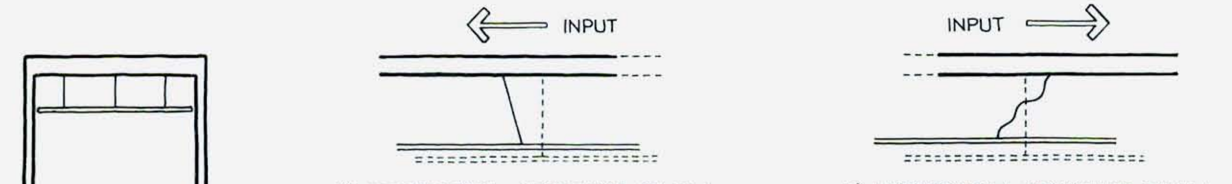
- The most flexible ceiling plane is constructed such that over a broad area, the plane will be capable of deflecting in a wave-like pattern with little or no damage.
- A moderately flexible ceiling plane can deflect without damage at a limited number of joints. Between the joints, however, the components cannot deflect without damage.
- The stiffest type of ceiling plane has rigid joints and stiff panels and thus can deflect only minimally without damage.

The mass of the ceiling plane will further alter its tendency to be stiff or flexible. Ceiling plane subsystems may be constructed of several different materials that vary in weight from the lightest acoustical tiles to relatively heavy double-layered gypsum board. Any of the available materials might be designed to produce relatively flexible or relatively stiff ceiling planes, but lighter materials are more likely choices for flexible designs, and heavier materials are more likely choices for stiff subsystems. The use of heavier materials will result in the ceiling plane behaving more as a stiff surface than a flexible one, especially in the case of semi-flexible subsystems, because of the effect of gravity. The use of lighter materials will result in semi-flexible subsystems acting much like flexible subsystems. Thus, from this point forward, only two distinct types of ceiling planes will be studied: "flexible ceiling planes" and "rigid ceiling planes."

Ceiling Suspension Subsystems



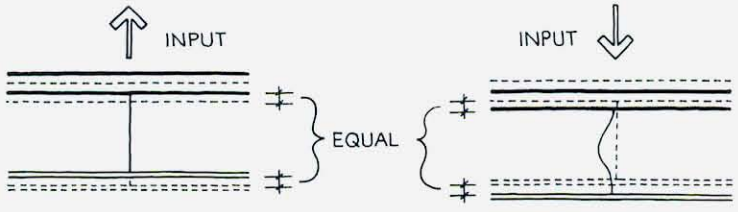
Because the mass of suspended ceiling systems is considered insignificant, mass will be constant for all types of suspension systems studied. However, stiffnesses vary for each type of subsystem: the variations are due to both the configuration of each subsystem and the stiffness of the individual components. Two different configurations, one unbraced and the other braced, are studied as generic types of suspension subsystems. Next, each configuration is considered, first, as if it were constructed of flexible components, and, second, as if it were constructed of stiff components. The potential responses of the resulting four possible types of suspension subsystems are then studied to determine the generic types of suspension subsystems that are acceptable in buildings subjected to earthquake input motions.



AT REST

A) HORIZONTAL RESPONSE, TIME t_1

B) HORIZONTAL RESPONSE, TIME t_2



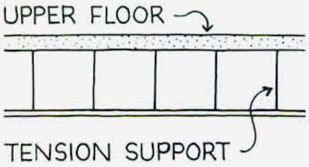
C) VERTICAL RESPONSE TO UPWARD MOTIONS

D) VERTICAL RESPONSE TO DOWNWARD MOTIONS (FLOATING)

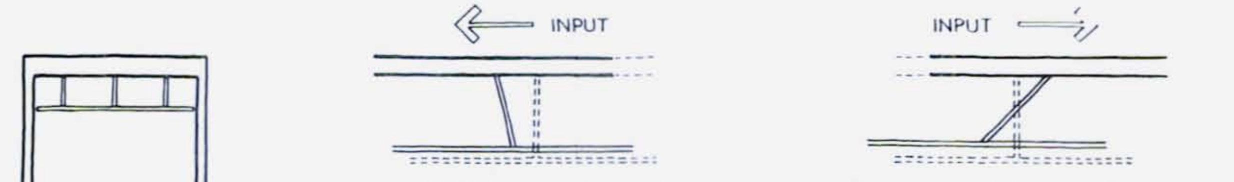
FIGURE 4-8. CEILING RESPONSE DUE TO UNBRACED FLEXIBLE SUSPENSION SUBSYSTEM (CEILING PLANE ASSUMED RIGID).

Unbraced configurations are composed of vertical members suspended from the upper floor at constant intervals.

Unbraced configurations are composed of vertical members suspended from the upper floor at constant intervals. The vertical components can be either tension members, in which case they are flexible, or tension/compression members, in which case they are stiff. Each type of system will have its own response to input motions and is described below:



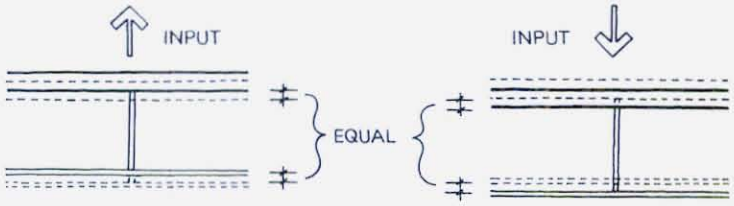
- Unbraced Flexible Suspension Subsystems (Figure 4-8). These subsystems have vertical support members that carry forces in tension only. Horizontal motions of the upper floor will result in the ceiling responding with both horizontal and vertical motions. Because the ceiling and the upper floor have different physical properties, and, hence, different periods of vibration, they may move out-of-phase, causing relative displacements between them (Figure 4-8a,b). The horizontal motions of the upper floor will result in the ceiling plane responding with vertical patterns of motion. Upward motion of the upper floor results in the ceiling being pulled upward with it (Figure 4-8c). Because of the inertia of the ceiling system, downward motion of the upper floor may result in the ceiling "floating" for an instant before it drops (Figure 4-8d). Periodic repetition of such motion may result in fatigue and failure. Some floating may also result from the ceiling's response to the upper floor's horizontal input motions.



AT REST

A) HORIZONTAL RESPONSE, TIME t_1

B) HORIZONTAL RESPONSE, TIME t_2



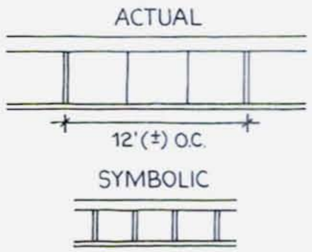
C) VERTICAL RESPONSE TO UPWARD MOTIONS

D) VERTICAL RESPONSE TO DOWNWARD MOTIONS

FIGURE 4-9. CEILING RESPONSE DUE TO UNBRACED RIGID SUSPENSION SUBSYSTEM (CEILING PLANE ASSUMED RIGID).

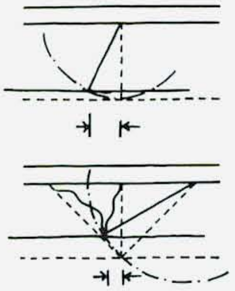
- Unbraced Rigid Suspension Subsystems (Figure 4-9). These subsystems have some vertical members that carry forces in both tension and compression, and some that carry forces in tension only. The margin diagram illustrates the actual configuration and the symbolic representation for it that will be used in this chapter. Horizontal and vertical motions of the upper floor will result in response patterns similar to those of the unbraced flexible support subsystem, except that the floating tendency will be considerably reduced for horizontal motions (Figure 4-9a,b), and the floating tendency will be nearly eliminated for vertical motions (Figure 4-9c,d).

UNBRACED RIGID SUSPENSION

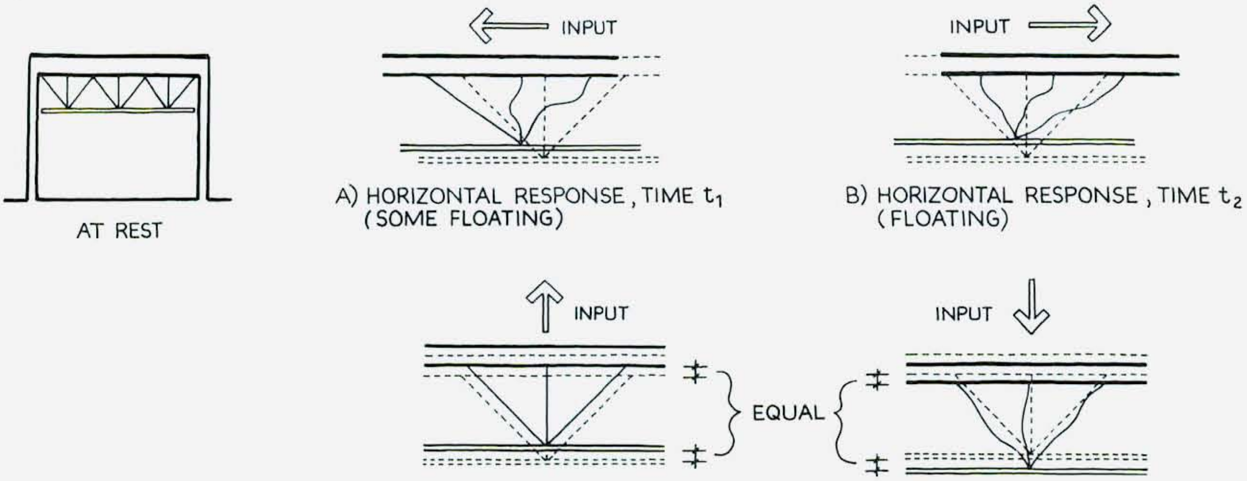


Braced configurations are composed of both vertical suspension members similar to those in the unbraced configurations and diagonal support members.

Braced configurations are composed of both vertical suspension members similar to those in the unbraced configurations and diagonal support members. The change in configuration caused by the addition of the diagonals makes some of the response patterns of the ceiling system different from those of the unbraced system. Within the group of braced suspension subsystems, the response of the ceiling will vary according to the stiffness of the vertical suspension components, as described below.



- Braced Flexible Suspension Subsystems (Figure 4-10). All suspension members of this subsystem carry forces in tension only. Because of the configuration of the subsystem -- the longer length of the diagonal tension braces that will control the path of the ceiling movement (see margin) -- the vertical displacement of the ceiling plane in response to the upper floor's horizontal input motions will be considerably greater than for either of the unbraced suspension systems. Consequently the ceiling plane will tend to float. But the diagonals will result in horizontal response patterns that more closely resemble the input motion patterns of the upper floor than is the case for either of the unbraced suspension systems.



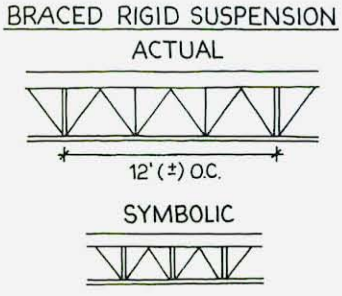
A) HORIZONTAL RESPONSE, TIME t_1 (SOME FLOATING)

B) HORIZONTAL RESPONSE, TIME t_2 (FLOATING)

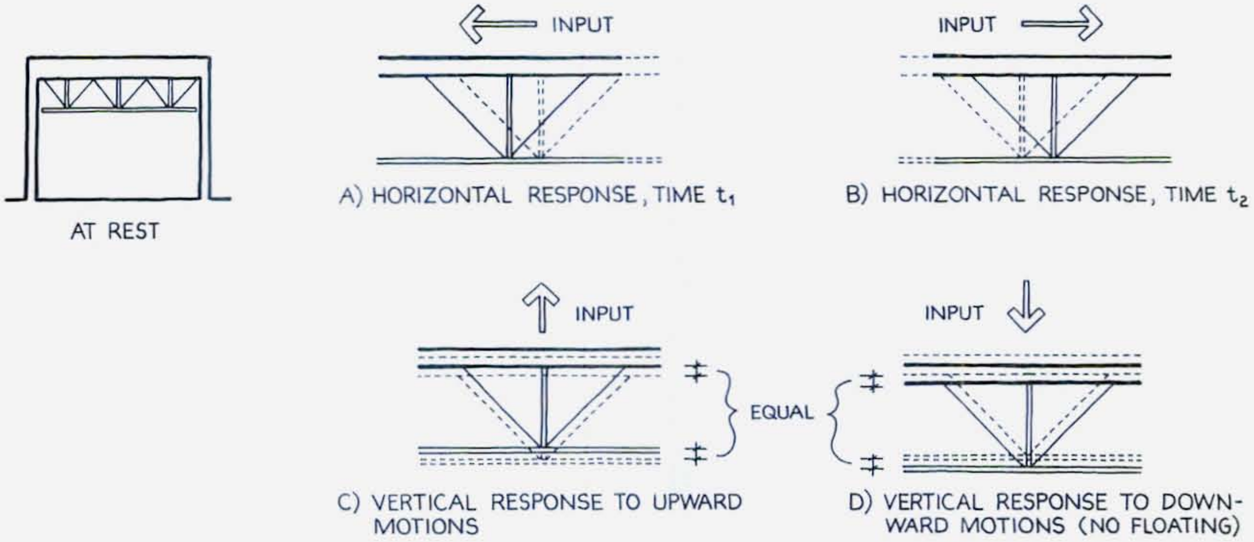
C) VERTICAL RESPONSE TO UPWARD MOTIONS

D) VERTICAL RESPONSE TO DOWNWARD MOTIONS (FLOATING)

FIGURE 4-10. CEILING RESPONSE DUE TO BRACED FLEXIBLE SUSPENSION SUBSYSTEM (CEILING PLANE ASSUMED RIGID).



- Braced Rigid Suspension Subsystems (Figure 4-11). These subsystems have some vertical members that carry forces in both tension and compression, some that carry forces in tension only, and diagonal tension braces. Only the vertical members of these suspension systems must be capable of transmitting forces in tension and compression for the entire system to respond in a rigid, truss-like manner. Horizontal input motions of the upper floor will result in the ceiling plane responding with the same horizontal motion patterns. The vertical compression members will prevent the ceiling from tending to "float" in response to vertical and horizontal motions induced by the upper floor. The ceiling will respond to the upper floor's vertical input motions with similar vertical motions.



AT REST

A) HORIZONTAL RESPONSE, TIME t_1

B) HORIZONTAL RESPONSE, TIME t_2

C) VERTICAL RESPONSE TO UPWARD MOTIONS

D) VERTICAL RESPONSE TO DOWNWARD MOTIONS (NO FLOATING)

FIGURE 4-11. CEILING RESPONSE DUE TO BRACED RIGID SUSPENSION SUBSYSTEM (CEILING PLANE ASSUMED RIGID).

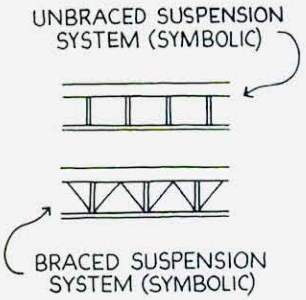
The "floating" tendency occurs in all flexible support systems, whether they are part of a braced or an unbraced configuration. This tendency can cause a chaotic bouncing of the ceiling plane that may result in major damage or even failure of the suspension members. For this reason the flexible-type support systems are considered unacceptable ceiling suspension subsystems and will not be discussed further in this chapter. Such systems cannot be designed to be compatible with other systems in buildings with either "flexible" or "stiff" responses. Flexible suspension systems can, however, be modified to respond similarly to rigid suspension systems if various kinds of service system components -- ducts, pipes, lighting fixtures, and so forth -- can be designed to perform as rigid bracing members and hence prevent floating.

Flexible-type support systems are considered unacceptable ceiling suspension subsystems and will not be discussed further in this chapter.

Thus the acceptable ceiling suspension systems are both rigid and are distinguished from each other according to their configuration, which will from this point forward be used to describe them:

Unbraced Rigid Support Subsystems = Unbraced Suspension Systems

Braced Rigid Support Subsystems = Braced Suspension Systems



Ceiling System Types

Combining the Unbraced and Braced suspension subsystems with both the Flexible and Rigid ceiling plane subsystems results in four distinct suspended ceiling types.

Combining the Unbraced and Braced suspension subsystems with both the Flexible and Rigid ceiling plane subsystems results in four distinct suspended ceiling types. The response of a ceiling type is dependent upon the interaction of its suspension subsystem and its ceiling plane, but cannot be obtained merely by combining the individual responses. The interaction of the combined subsystems must be analyzed to determine their response as a suspended ceiling type. Damage caused by any ceiling type's response to input motions can occur in the following ways:

- The ceiling may damage itself if its response is out-of-phase with the input motions to it. The ceiling may hammer against another component, may be distorted by its own displacement relative to another system, or it may not be able to endure the shear, axial, or bending forces imposed upon it. In any of these cases damage may occur to the suspension subsystem, the ceiling plane, or the joint between the two.
- The ceiling may damage another system by hammering against it or puncturing it, subjecting it to excessive shear, bending, or axial forces, or abnormally distorting its configuration.
- The ceiling may damage its interface with other systems. Such damage may result in loss of support of one or both systems, or in the hammering of the two systems against each other.

Depending upon the response patterns of the system, the strength of its individual components, and the design of its interfaces with other systems, any of the above types of damage may occur to the basic ceiling types described below.

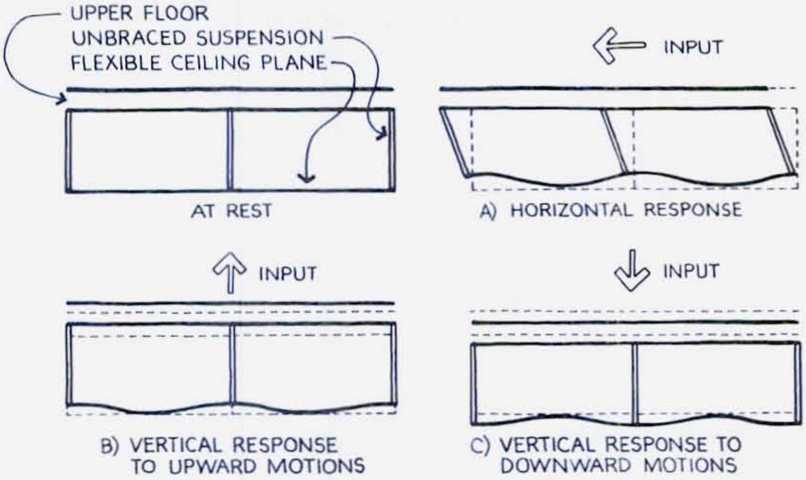


FIGURE 4-12. CEILING TYPE: FLEXIBLE CEILING PLANE - UNBRACED SUSPENSION.

Flexible Ceiling Plane - Unbraced Suspension. Horizontal input motions of the upper floor resulting in vertical displacement of the ceiling system will probably cause the ceiling to deflect in a wave-like pattern (Figure 4-12a). The ceiling will also displace horizontally in a pattern that may be out-of-phase with the upper floor's displacements. Racking of the ceiling plane frame may occur due to changes in the directions of the motions and may result in panels being dislodged. Vertical upward and downward motions of the upper floor will be followed directly by the ceiling plane at the points of suspension, but will be delayed between these points, causing wave-like deflections (Figure 4-12b,c). In order for this system to respond with little or no damage when located in a relatively flexible building, the design requirements are as follows:

- Interface conditions should permit the ceiling system to respond to the horizontal motions of adjacent systems. The ceiling system's response to horizontal input motions of the upper floor must be compatible with the horizontal motions of adjacent systems.

- Interface conditions at restrictive supports should not permit the ceiling system to respond to vertical motions of adjacent systems. The ceiling system's response motions must be equal and in-phase with the vertical input motions of the upper floor.

- Interface conditions at nonrestrictive supports may permit the ceiling system to respond to the vertical motions of adjacent systems. The ceiling system's response to vertical input motions of the upper floor must be compatible with the vertical motions of adjacent systems.
- The individual components of the ceiling plane subsystem should be installed in a manner that will prevent their being dislodged by vertical motions or racking.

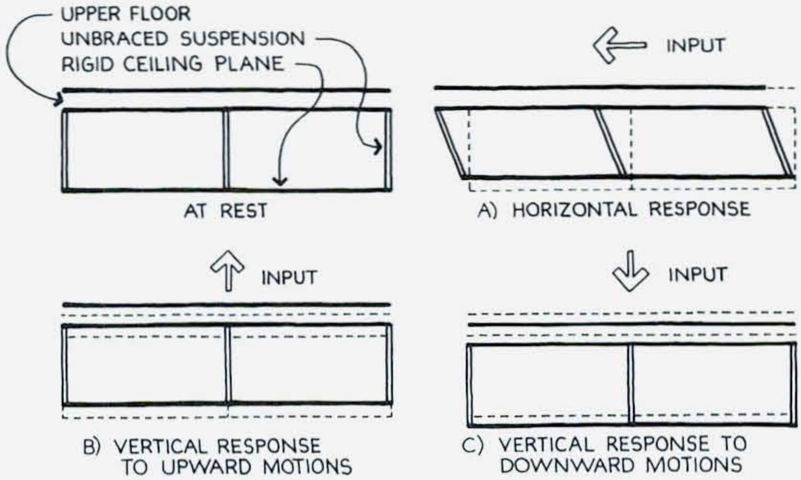


FIGURE 4-13. CEILING TYPE: RIGID CEILING PLANE - UNBRACED SUSPENSION.

Rigid Ceiling Plane - Unbraced Suspension. Horizontal input motions of the upper floor would probably cause the ceiling plane to respond with horizontal and vertical displacements (Figure 4-13a). The ceiling plane would not deflect significantly as it displaced vertically, and would displace horizontally in a pattern out-of-phase with the motions of the upper floor. The ceiling system as a whole would respond directly to the vertical input motions of the upper floor (Figure 4-13b,c). In order for this system to respond with little or no damage when located in a relatively flexible building, the design requirements are as follows:

- Interface conditions should permit the ceiling system to respond to the horizontal motions of adjacent systems. The ceiling system's response to horizontal input motions of the upper floor must be compatible with the horizontal motions of adjacent systems.

- Interface conditions should not permit the ceiling system to respond to vertical motions of adjacent systems. The ceiling system's response motions must be equal and in-phase with the vertical input motions of the upper floor.
- Individual components of the lay-in tile variety of ceiling plane should be installed in a manner that will prevent their being dislodged due to vertical motions. This problem does not exist for the continuous plane variety of ceiling planes, such as gypsum board or laminated plastic.

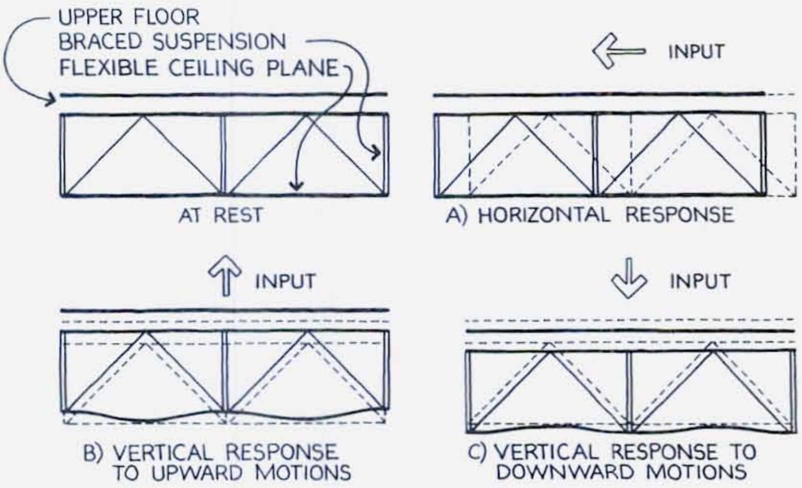


FIGURE 4-14. CEILING TYPE: FLEXIBLE CEILING PLANE - BRACED SUSPENSION.

Flexible Ceiling Plane - Braced Suspension. The ceiling plane would respond to horizontal input motions of the upper floor with displacements similar to and in-phase with those of the upper floor (Figure 4-14a). Racking of the ceiling plane frame may occur if the frame is attached to partitions and the upper and lower floors move out-of-phase. Vertical displacements due to vertical input motions of the upper floor would be similar at restrictive locations, with some flexure of the ceiling plane between these points. (Figure 4-14b,c). In order for this system to respond with little or no damage when located in a relatively flexible building, the design requirements are as follows:

- Interface conditions should not permit the ceiling system to respond to horizontal motions of adjacent systems.

The ceiling system's response motions must be equal and in-phase with the horizontal input motions of the upper floor.

- Interface conditions at restrictive supports should not permit the ceiling system to respond to vertical motions of adjacent systems. The ceiling system's response motions must be equal and in-phase with the vertical input motions of the upper floor.
- Interface conditions at nonrestrictive supports may permit the ceiling system to respond to the vertical motions of adjacent systems. The ceiling system's response to vertical input motions of the upper floor must be compatible with the vertical motions of adjacent systems.
- The components of the ceiling plane subsystem should be installed in a manner that will prevent them from being dislodged due to vertical motions or racking.

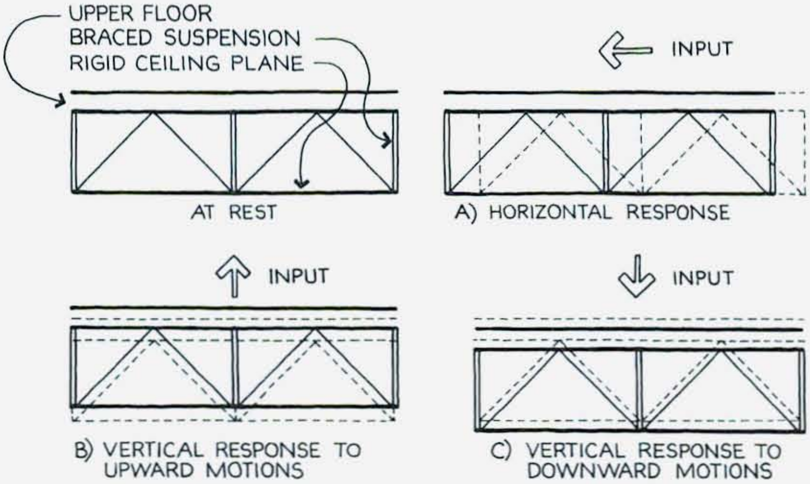
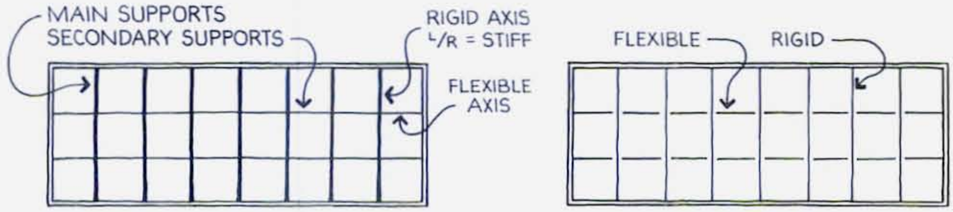


FIGURE 4-15. CEILING TYPE: RIGID CEILING PLANE - BRACED SUSPENSION.

Rigid Ceiling Plane - Braced Suspension. The ceiling plane would respond to horizontal and vertical input motions of the upper floor with displacements similar and in-phase with those of the upper floor (Figure 4-15). In order for this system to respond with little or no damage when located in a relatively flexible building, the design requirements are as follows:

- Interface conditions should not permit the ceiling system to respond to horizontal or vertical motions of adjacent systems. The ceiling system's response motions must be equal and in-phase with the horizontal and vertical input motions of the upper floor.

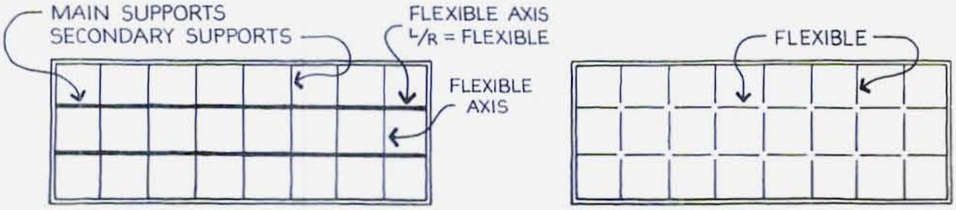
- Individual components of the lay-in tile variety of ceiling plane should be installed in a manner that will prevent their being dislodged due to vertical motions. This problem does not exist for the continuous plane variety of ceiling planes, such as gypsum board or laminated plastic.



DIRECTION AND LENGTH OF MAIN SUPPORTS

FLEXIBILITY OF AXES

MAIN SUPPORTS PARALLEL TO NARROW DIMENSION



DIRECTION AND LENGTH OF MAIN SUPPORTS

FLEXIBILITY OF AXES

MAIN SUPPORTS PARALLEL TO LONG DIMENSION

FIGURE 4-16. LONG, NARROW ROOM CEILING PLAN: EFFECT OF DIRECTION AND LENGTH OF SUPPORT MEMBER ON ITS FLEXIBILITY.

Ceilings are often designed and installed such that their ceiling type is different in one axis from what it is in the other axis because of variations in the stiffness of the ceiling plane.

Ceilings are often designed and installed such that their ceiling type is different in one axis from what it is in the other axis because of variations in the stiffness of the ceiling plane. For example, a typical suspended acoustical tile ceiling will normally be constructed with main tile support members running in one direction, and with secondary tile support members running perpendicular to them. Because the main members are usually stiffer than the secondary members, the flexibility of the ceiling varies in the two axes. In some installations the ceiling plane may be stiff in the axis parallel to the main supports and flexible in the axis parallel to the secondary supports (Figure 4-16). Although not normally designed as such, the suspension method can also be different for each of the two axes: a fully braced system may be installed in one direction but not the other, again varying the flexibility of the installation (Figure 4-17). This condition may occur by accident if the diagonal suspension wires are installed with unequal tension, which is undesirable, or by design if the conditions are such that bracing is desirable in only one axis. Because the ceiling plane and suspension subsystems can be varied in each of their two axes, the number of conditions for which the ceiling can be designed to be compatible is increased.

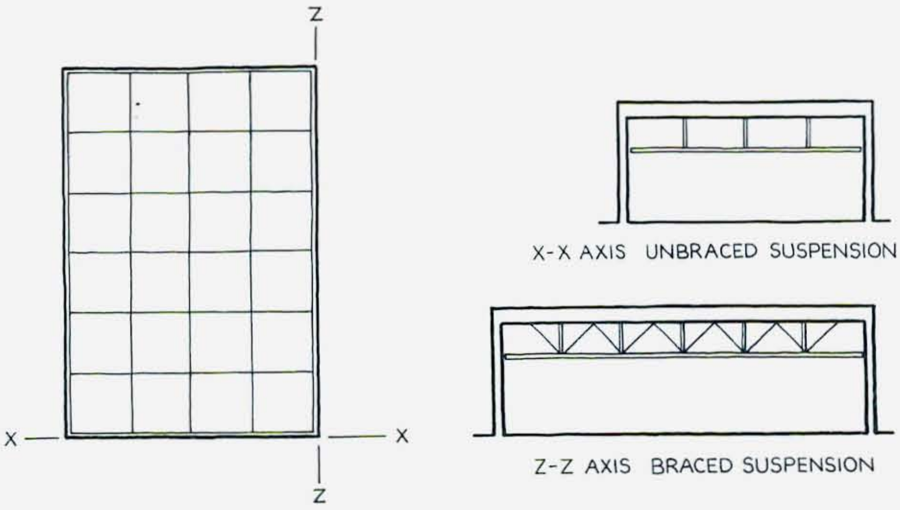


FIGURE 4-17. DIFFERENT SUSPENSION SUBSYSTEMS FOR DIFFERENT AXES OF CEILING SYSTEM.

Generic Ceiling Systems and Their Design Requirements

The reader may wish at this point to refer back to Figure 4-6 to review the logical development of the different ceiling types. Figure 4-7 described two-dimensionally the ten generic ceiling systems that may be designed to be dynamically compatible in buildings with "flexible" responses. Based upon the design requirements for different ceiling types outlined above, design requriements can be formulated for the ten generic ceiling systems. Design requirements for horizontal motions of the ceiling system are affected by whether or not the ceiling system is braced. Design requirements for vertical motions are dependent upon the flexibility of the ceiling plane and whether or *restrictive support*

nonrestrictive support

not the adjacent system(s) is(are) connected at a restrictive or a nonrestrictive support. A restrictive support is provided by either a tension hanger, a compression strut, or a rigid ceiling plane frame. A nonrestrictive support is one that occurs between compression struts or tension hangers along a flexible ceiling plane frame. Thus the interface condition between a partition and a restrictive support must allow for relative displacements in the vertical direction or damage will occur from the two systems either hammering together or pulling apart.

Ceiling systems are assumed to be subordinate to the upper floor and to adjacent partition systems. This assumption is based upon the physical properties of the ceiling system: suspended ceiling systems are relatively lightweight and relatively flexible compared to the Dynamic Structure and partition systems. Design requirements for horizontal or vertical motions essentially permit the ceiling system to respond to input motions of adjacent systems or prohibit it from doing so; more specifically, the design requirements for horizontal motions in both axes and vertical motions at restrictive supports or nonrestrictive supports are always one of the following:

A: Interface conditions should not permit the ceiling system to respond to motions of adjacent systems. The ceiling system's response motions must be equal and in-phase with the input motions of the upper floor.

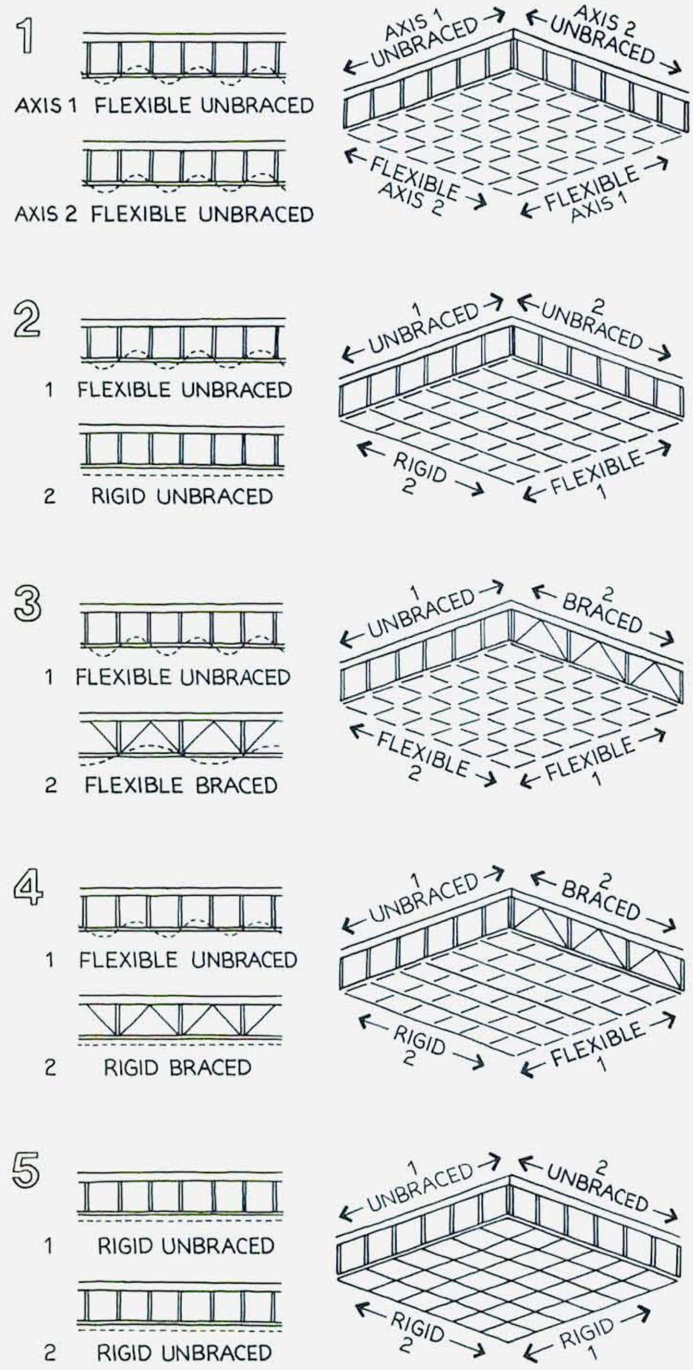
B: Interface conditions should permit the ceiling system to respond to the motions of adjacent systems. The ceiling system's response to input motions of the upper floor must be compatible with the motions of adjacent systems.

Whenever a system is located at a vertical support of the ceiling, the interface conditions must permit the ceiling system to respond to the vertical input motions of the upper floor with equal and in-phase motions.

In addition to requirements A and B, ceiling systems must remain stable when subjected to seismic loads.

The design requirements for horizontal and vertical motions in both axes for each of the ten ceiling systems are summarized in Figure 4-18. Regardless of the system, whenever an adjacent system is located at a restrictive support, the interface conditions must permit the ceiling system to respond to the vertical input motions of the upper floor with equal and in-phase motions (Design Requirement A). In addition to Requirements A and B, ceiling systems must remain stable when subjected to seismic loads. Braced ceiling types are inherently stable, but unbraced

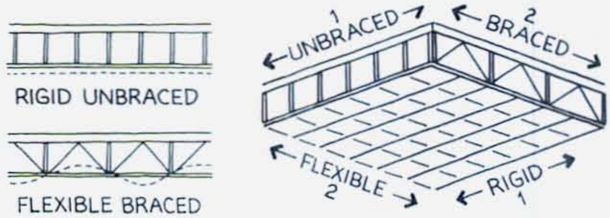
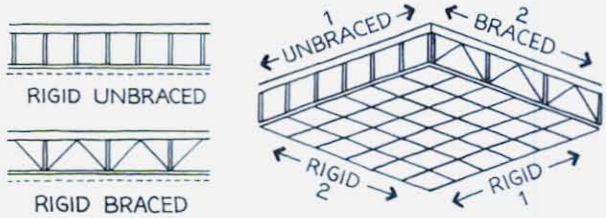
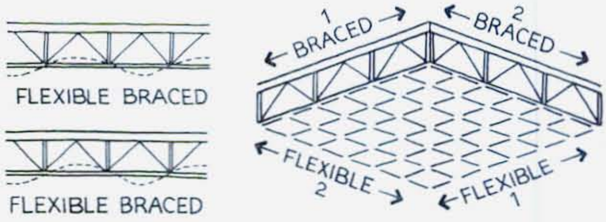
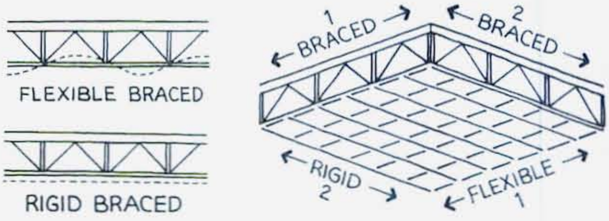
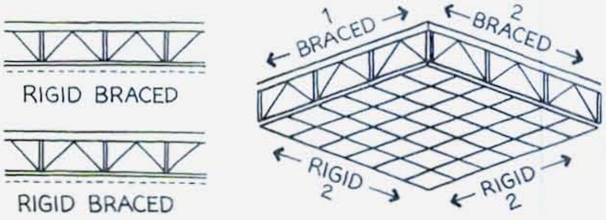
A INTERFACE CONDITIONS SHOULD NOT PERMIT THE CEILING SYSTEM TO RESPOND TO MOTIONS OF ADJACENT SYSTEMS. THE CEILING SYSTEM'S RESPONSE MOTIONS MUST BE EQUAL AND IN-PHASE WITH THE INPUT MOTIONS OF THE UPPER FLOOR.



		HORIZONTAL MOTIONS		VERTICAL MOTIONS			
				RESTRICTIVE OR NONRESTRICTIVE SUPPORT		NONRESTRICTIVE SUPPORT ONLY	
		AXIS 1	AXIS 2	AXIS 1	AXIS 2	AXIS 1	AXIS 2
1	AXIS 1 FLEXIBLE UNBRACED AXIS 2 FLEXIBLE UNBRACED	B	B	A	A	B	B
2	1 FLEXIBLE UNBRACED 2 RIGID UNBRACED	B	B	A	A	A	B
3	1 FLEXIBLE UNBRACED 2 FLEXIBLE BRACED	B	A	A	A	B	B
4	1 FLEXIBLE UNBRACED 2 RIGID BRACED	B	A	A	A	A	B
5	1 RIGID UNBRACED 2 RIGID UNBRACED	B	B	A	A	A	A

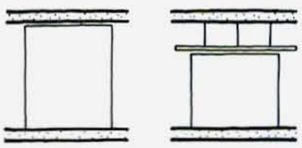
FIGURE 4-18. DESIGN REQUIREMENTS FOR GENERIC CEILING SYSTEMS.

B INTERFACE CONDITIONS SHOULD PERMIT THE CEILING SYSTEM TO RESPOND TO MOTIONS OF ADJACENT SYSTEMS. THE CEILING SYSTEM'S RESPONSE TO INPUT MOTIONS OF THE UPPER FLOOR MUST BE COMPATIBLE WITH THE MOTIONS OF ADJACENT SYSTEMS.

			HORIZONTAL MOTIONS		VERTICAL MOTIONS			
					RESTRICTIVE OR NONRESTRICTIVE SUPPORT		NONRESTRICTIVE SUPPORT ONLY	
			AXIS 1	AXIS 2	AXIS 1	AXIS 2	AXIS 1	AXIS 2
⑥	1 RIGID UNBRACED 2 FLEXIBLE BRACED		B	A	A	A	B	A
⑦	1 RIGID UNBRACED 2 RIGID BRACED		B	A	A	A	A	A
⑧	1 FLEXIBLE BRACED 2 FLEXIBLE BRACED		A	A	A	A	B	B
⑨	1 FLEXIBLE BRACED 2 RIGID BRACED		A	A	A	A	B	A
⑩	1 RIGID BRACED 2 RIGID BRACED		A	A	A	A	A	A

ceiling types must be stabilized by an adjacent system or systems. An application of the design requirements for specific ceiling and partition systems will be presented later in this chapter and will include a discussion of stability.

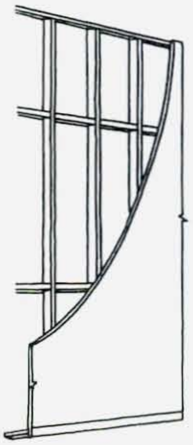
PARTITIONS



Partitions studied in this chapter are representative of the large majority of common non-load-bearing interior partitions.

The term partition may be used to refer to a wide range of interior space dividers of all sizes and from the most temporary to the most permanent. In this study the term partition will apply to a narrow range of systems: the most temporary space dividers are excluded because they more closely resemble furnishings, and partitions that would significantly influence the response of the Dynamic Structure (that is Coupled Elements) are also excluded. The remaining partitions studied in this chapter are representative of the large majority of common non-load-bearing interior partitions.

partition system



A "partition system," hereafter simply called a "partition," is a three-dimensional sandwich composed of a frame and facing materials. The frame may be metal or wood studs of different sizes, gauges, and heights, and with varying spacing and bracing configurations. The facing materials may be gypsum board, lath and plaster, plywood, laminated plastic, fibreboard, metal, and so forth.

All partitions share some important characteristics. With respect to the Dynamic Structure:

- All partitions in this study are Uncoupled Elements.
- The dead loads of partitions are carried directly by the lower floor of the Dynamic Structure (hereafter simply called the "lower floor"). Partitions may be designed to be supported by the upper floor, columns, or walls, or by special subframing systems, all methods that require special design and installation techniques. Such specialized designs are not included because this study analyzes typical systems with the goal of designing them for improved seismic performance.
- Partitions will always respond to motions induced by the lower floor.

- Any attempt to restrain partitions so that they cannot respond to the input motions of the lower floor will result in damage either to the partitions, or to the connections at their interfaces.

With respect to the partition's own physical properties:

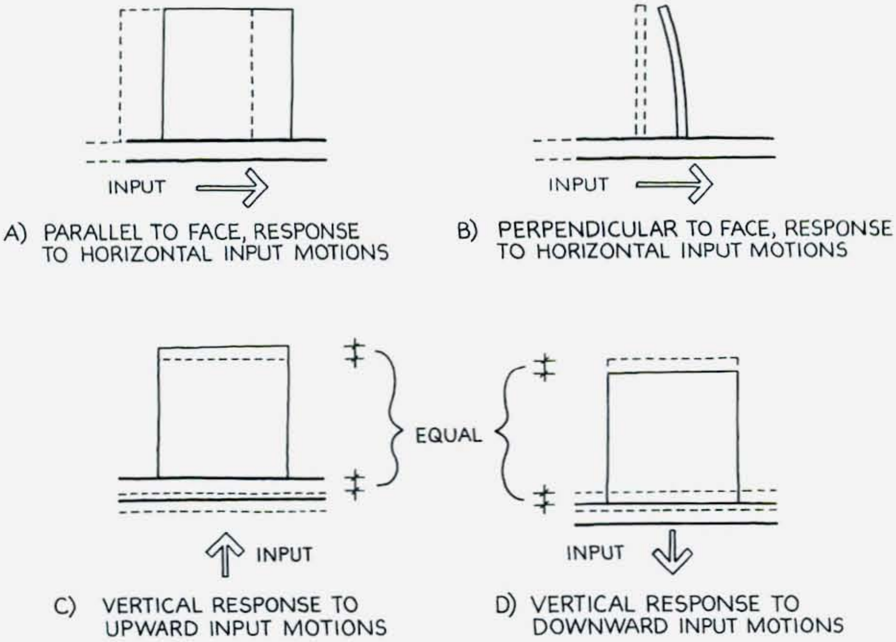
- The mass of one partition is considered to be similar enough to the mass of any other partition so that the relative mass of the two systems need not be considered in analyzing and designing them.
- Only those partitions that have interfaces with the ceiling system or the upper floor are examined in this study.

The partition as a whole is considered to be stable when subjected to motions parallel to its facing and unstable when subjected to motions perpendicular to its facing.

Partitions are capable of deflecting parallel to the plane of their facing a distance equal to that which the facing material alone can deflect without damage. Deflection parallel to the facing material of a partition (rigid axis) is assumed to be none, since the amount may vary but is always of a very small magnitude, say 1/16" in four feet. The partition will, however, be capable of significantly greater deflections in the direction perpendicular to its facing (flexible axis) because of its configuration. The partition as a whole is considered to be stable when subjected to motions parallel to its facing and unstable when subjected to motions perpendicular to its facing.

The response of partitions to input motions would probably be as follows:

- Parallel to its facing (rigid axis) and along its full height the partition will respond to horizontal input motions with horizontal motions that are equal and in-phase with the input motions of the lower floor (Figure 4-19a).
- Perpendicular to its facing (flexible axis) the partition will respond at its base with horizontal motions similar to and in-phase with the input motions of the lower floor. At its top the partition may respond with horizontal motions that are out-of-phase with the horizontal input motions of the lower floor (Figure 4-19b).
- The partition will respond to vertical input motions, both upward and downward, with motions that are similar and in-phase (Figure 4-19c,d).



A) PARALLEL TO FACE, RESPONSE TO HORIZONTAL INPUT MOTIONS

B) PERPENDICULAR TO FACE, RESPONSE TO HORIZONTAL INPUT MOTIONS

C) VERTICAL RESPONSE TO UPWARD INPUT MOTIONS

D) VERTICAL RESPONSE TO DOWNWARD INPUT MOTIONS

FIGURE 4-19. PARTITION RESPONSE TO INPUT MOTIONS OF THE LOWER FLOOR.

Design Requirements for Partitions

Design requirements for partitions are based upon their flexibility parallel to the plane of their facing and perpendicular to the plane of their facing. In this study partitions are assumed to be rigidly attached to the lower floor; hence, the base of a partition must respond to the input motions of the lower floor with equal and in-phase motions. However, depending upon the axis of the partition, the response of the top of the partition may or may not be similar to the motions of the base and the lower floor. A partition can deflect in the perpendicular axis, if necessary, but not in the parallel axis. Design requirements for partitions are based upon their flexibility in their parallel and perpendicular axes, and are shown in Figure 4-20 below. In addition to Design Requirements C and D, partitions must remain stable when subjected to seismic loads. Stability will be discussed following the next section on interface conditions.

C - INTERFACE CONDITIONS SHOULD NOT ALLOW THE PARTITION TO RESPOND TO THE MOTIONS OF ADJACENT SYSTEMS. RESPONSE MOTIONS MUST BE EQUAL AND IN-PHASE WITH THE INPUT MOTIONS OF THE LOWER FLOOR.

D - INTERFACE CONDITIONS SHOULD ALLOW PARTITION TO RESPOND TO THE MOTIONS OF ADJACENT SYSTEMS. THE PARTITION'S RESPONSE TO INPUT MOTIONS OF THE LOWER FLOOR MUST BE COMPATIBLE WITH THE MOTIONS OF ADJACENT SYSTEMS.

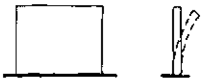
	HORIZONTAL MOTIONS		VERTICAL MOTIONS
	PARALLEL TO FACING	PERPENDICULAR TO FACING	
	C	D	C

FIGURE 4-20. BASIC DESIGN REQUIREMENTS FOR PARTITIONS.

INTERFACE CONDITIONS OF CEILING SYSTEMS AND PARTITIONS

The previous sections of this chapter have discussed the importance of a system's physical properties in determining its interaction with other systems. Equally important is the interface between any two systems, since only through this interface can motions of one system be transmitted to another system. An interface is the surface that forms the common boundary between two systems (Figure 4-21) and refers only to location and not to a type of connection. If one can ascertain whether motion should be transmitted through a given interface, and, if so, in what directions, then details can be designed to accommodate those motions.

If one can ascertain whether motion should be transmitted through a given interface and, if so, in what directions, then details can be designed to accommodate those motions.

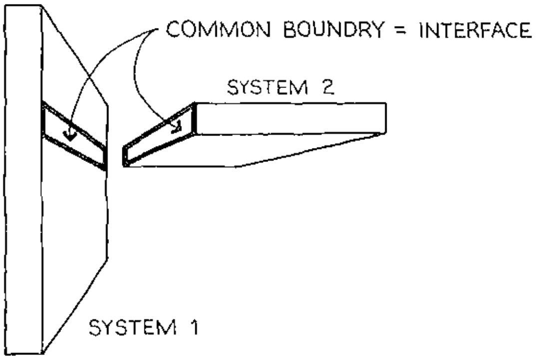


FIGURE 4-21. INTERFACE BETWEEN TWO SYSTEMS.

The physical properties of a system determine its response to motions transmitted to it, its potential degree of influence on the response of other systems, and its ability to respond with little or no damage. These factors, described previously for ceiling systems and partitions, determine whether motion should be transmitted to a system through a given interface, and if so, in what directions. The interface between two systems can be detailed in several ways, and the type of detail will control the transmittance of different motions through the interface. This section focuses on the development of an approach to the design of interface details that will permit motions to be transmitted only in the directions that are compatible with other systems.

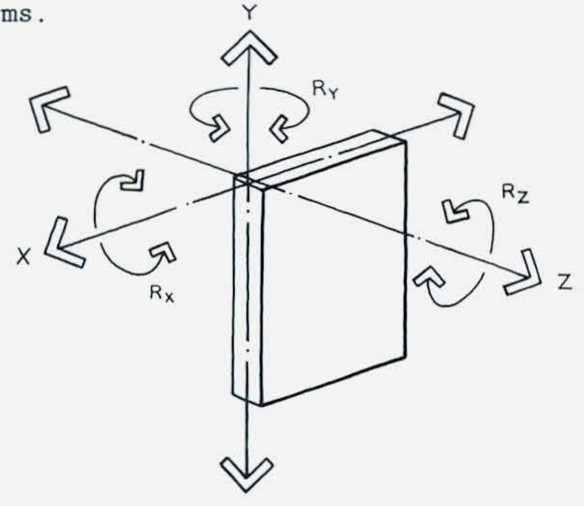
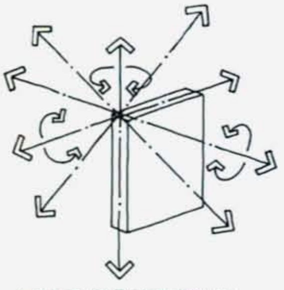


FIGURE 4-22. THREE ORTHOGONAL REFERENCE AXES FOR AXIAL AND ROTATIONAL MOTIONS.

Directions of Motions

Any system, whether it is a part of the Dynamic Structure (DynS), a Coupled Element (CpEl), or an Uncoupled Element (UncEl), is three-dimensional. Although motions can occur in an infinite number of directions, they may be more conveniently represented by the three orthogonal axes of a given system, either as axial or rotational motions (Figure 4-22).



MULTIDIRECTIONAL MOTIONS

INTERFACE AT SIDE
INTERFACE AT FACE (VERTICAL)
INTERFACE AT BOTTOM
INTERFACE AT FACE (HORIZONTAL)
INTERFACE AT TOP

FIGURE 4-23. EXAMPLES OF POSSIBLE INTERFACE LOCATIONS FOR A SINGLE PARTITION SYSTEM.

Interface Locations

Any system may have an interface with another system at any location. For example, a partition may have an interface with another system at any of its edges. A partition may also have an interface with another system at any point along its face, such as a vertical interface with another partition, a wall, or a column, or a horizontal interface with a ceiling, ductwork, or piping (Figure 4-23). Because of the large number of interface locations and the variations in the physical properties of systems and the multidirectional motions to which systems may be subjected, a huge number of different interface conditions exists. For purposes of analysis, the conditions may be defined by their motions in three dimensions, and then applied to different systems and interface locations.

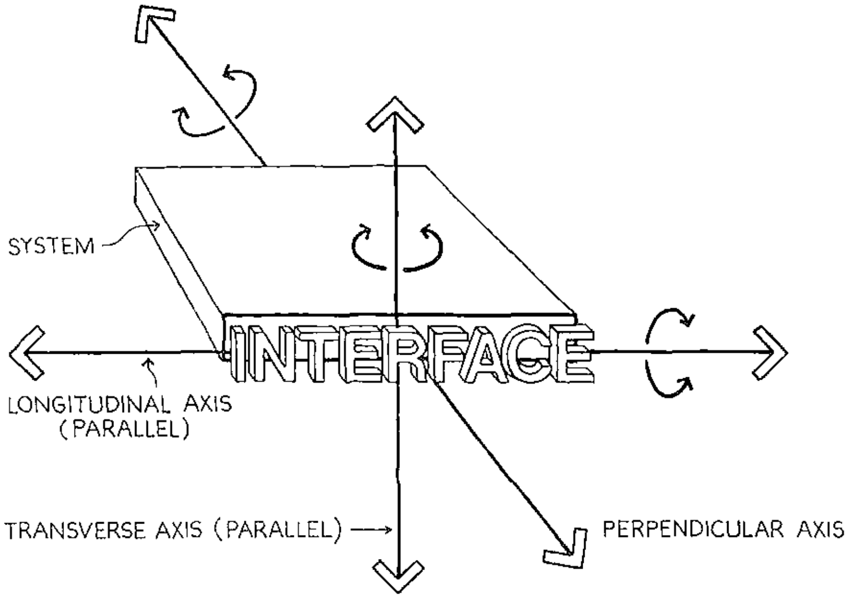


FIGURE 4-24. REFERENCE AXES FOR DIRECTIONS OF MOTION TRANSMITTANCE AND NONTRANSMITTANCE.

Eight Different Interface Conditions

For any interface there exists a unique set of motions, some of which will and some of which will not be transmitted between systems. Motions are transmitted in the two axes that are parallel to the plane of the interface and in the third axis that is perpendicular to the plane of the interface. As Figure 4-24 illustrates, one of the axes parallel

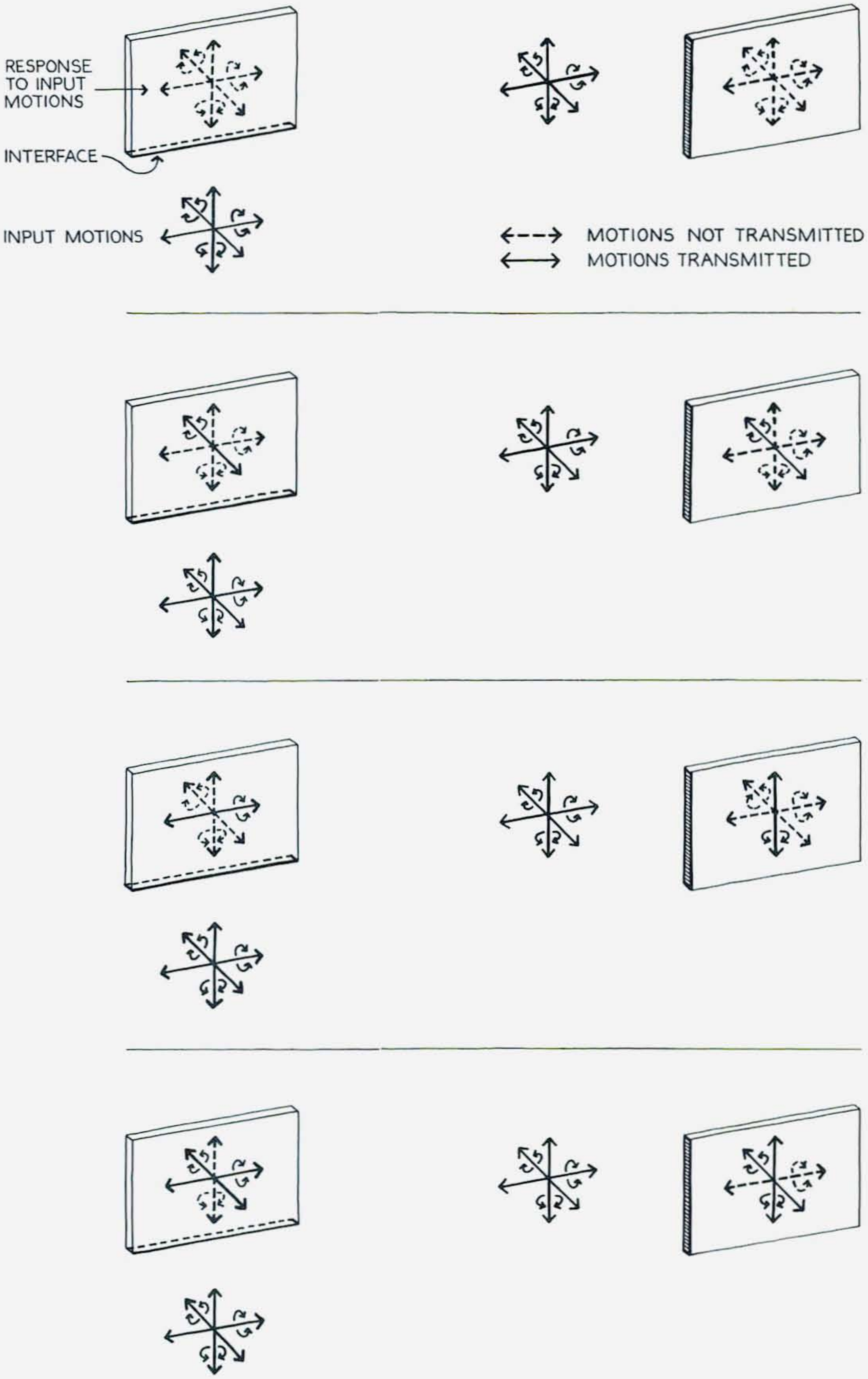


FIGURE 4-25. DIAGRAMS OF MOTION TRANSMITTANCE AND NONTRANSMITTANCE THROUGH INTERFACES.

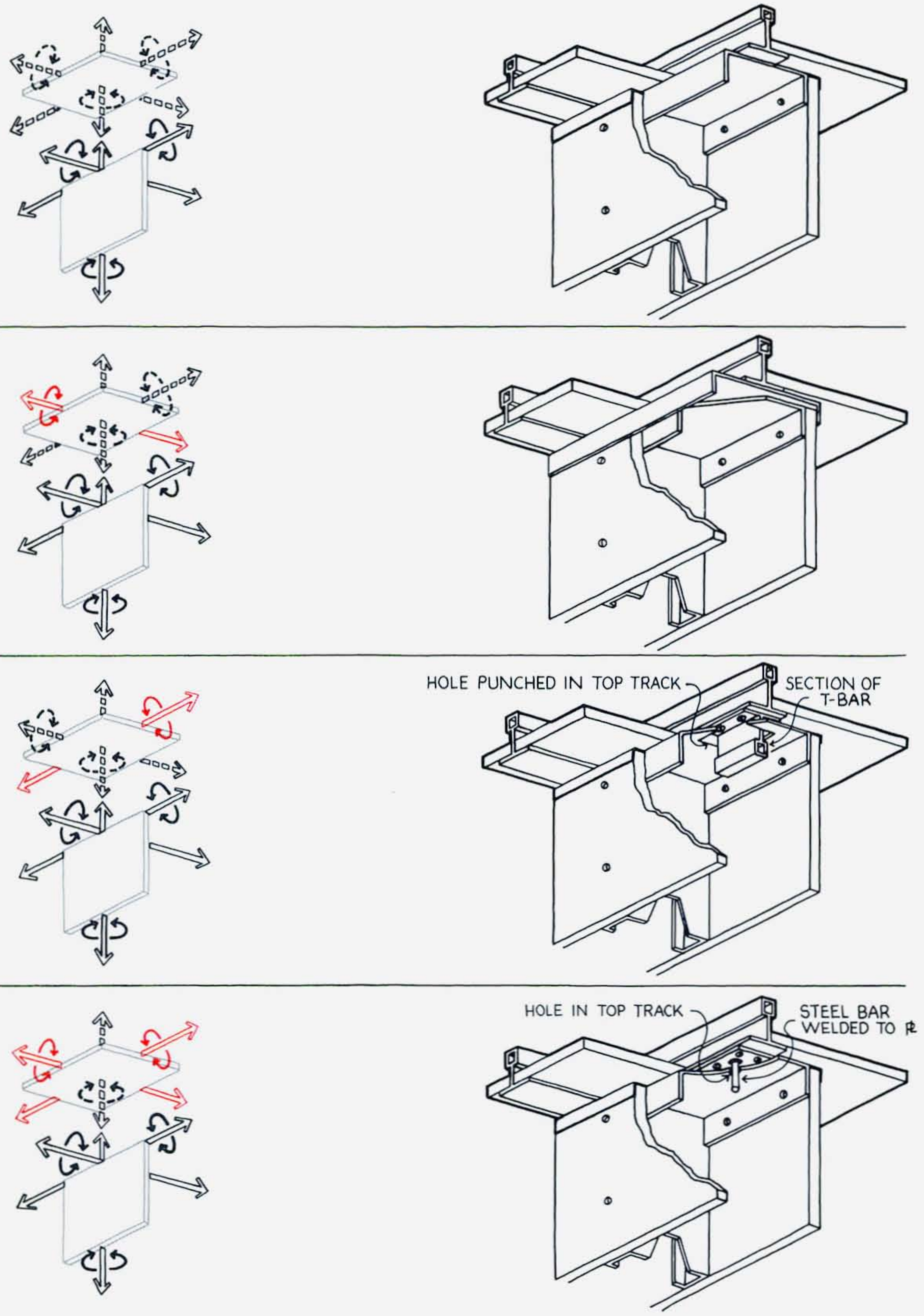
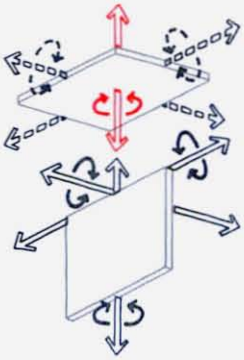
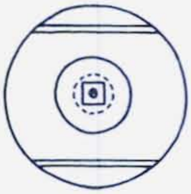
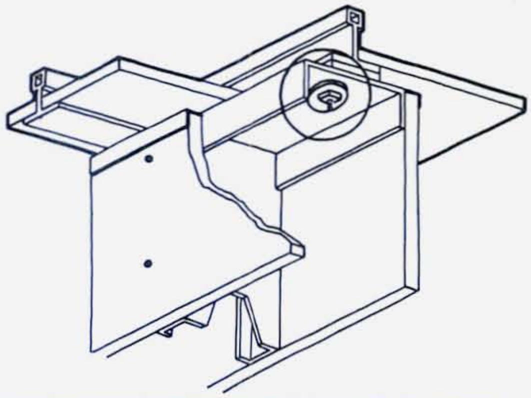
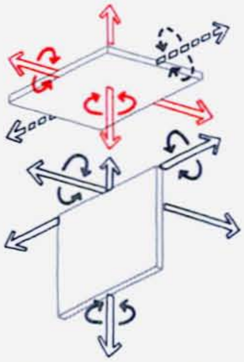


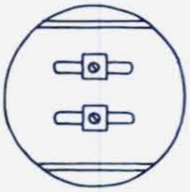
FIGURE 4-26. SAMPLE DETAILS ILLUSTRATING MOTION TRANSMITTANCE SYMBOLS FOR THE EIGHT DIFFERENT INTERFACE CONDITIONS.

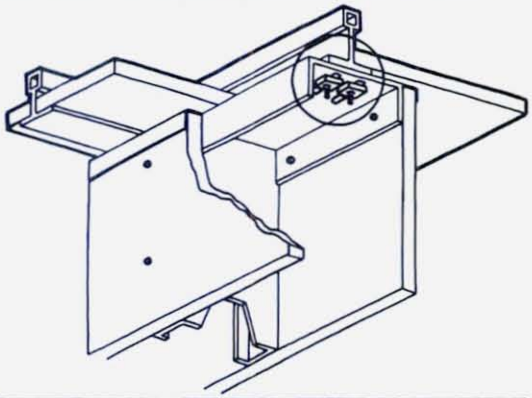


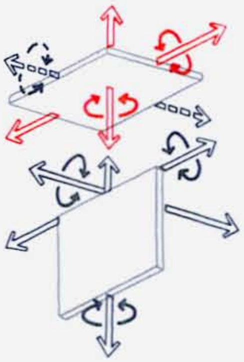


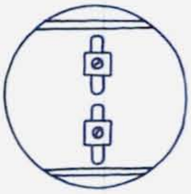


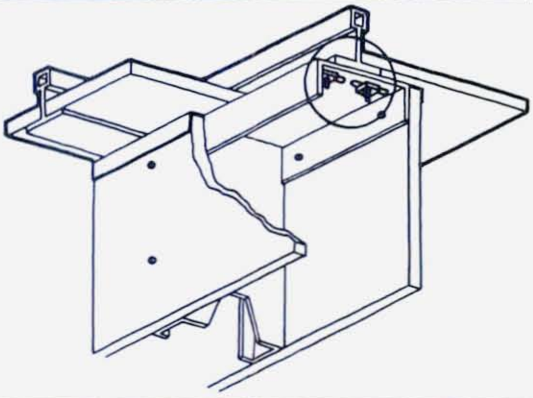


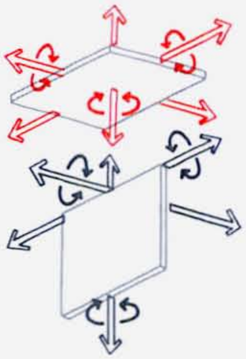


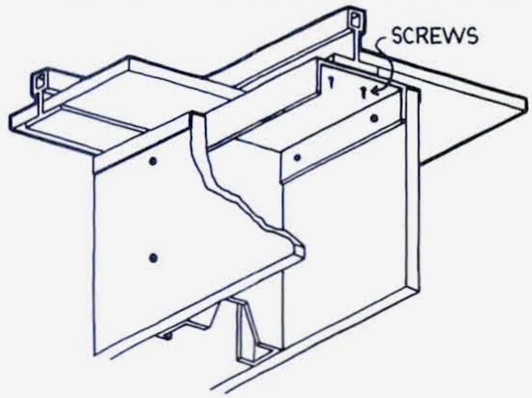











SCREWS

longitudinal, transverse, and perpendicular axes

to the interface will be called the "longitudinal parallel axis" or simply the "longitudinal axis," and the other will be called the "transverse parallel axis," or simply, the "transverse axis." The axis perpendicular to the plane of the interface is the "perpendicular axis." Motions may or may not be transmitted in any one of these axes, and hence there are eight possible combinations of motion transmittance and nontransmittance. Figure 4-25 illustrates the eight different combinations of motion transmittance, both axial and rotational, for an interface at the bottom of a partition and for one at the side of a partition.

The eight different interface conditions may be further illustrated by their actual application to the design of details of the interface between a partition and a ceiling system. Figure 4-26 illustrates how the different interface conditions can be accommodated by a design detail. Each detail has identical systems and the same interface location so that the difference in detailing for various interface conditions may be easily understood.

DEGREES OF INTERACTION IN DYNAMIC ENVIRONMENTS FOR CEILING SYSTEMS AND PARTITIONS

Any ceiling system or partition has a Dynamic Environment for which it must be designed. The components and systems of that Dynamic Environment will affect the response of a ceiling system or partition to varying degrees, and the interaction between the systems can be described as dominant, subordinate, or mutual. A hierarchy of interaction exists within a particular Dynamic Environment and this hierarchy for the ceiling systems and partitions analyzed in this study is outlined in Figure 4-27. In this diagram, mutual interaction is further defined according to the amount of influence each system has on another system. The amount of influence may be equal, or one system's contribution to the mutual interaction may be moderate, or small, compared to the more significant contribution of another system. The dominant/subordinate relationship symbolizes the relatively large influence of the dominant system and the relatively small influence of the subordinate system.

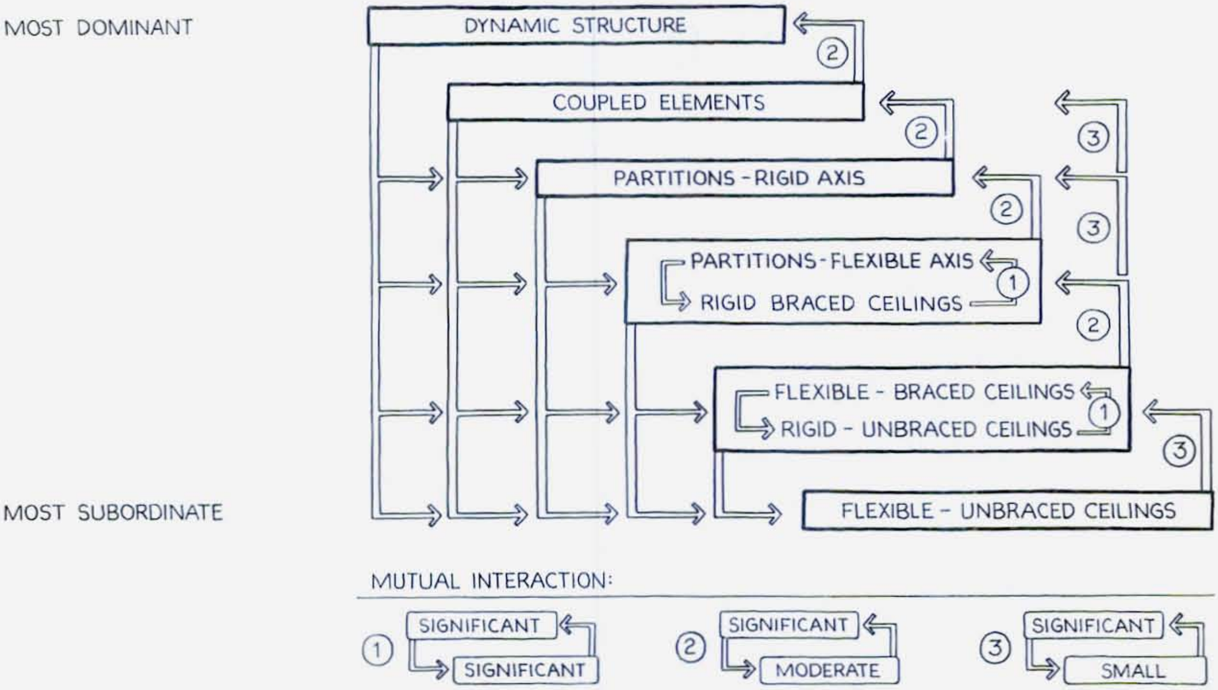


FIGURE 4-27. HIERARCHY OF INTERACTION FOR CEILING SYSTEMS AND PARTITIONS IN THIS CHAPTER.

DESIGNING COMPATIBLE CEILING SYSTEMS AND PARTITIONS FOR THEIR DYNAMIC ENVIRONMENTS

Given the physical properties of the ceiling systems and partitions in this chapter and the eight possible interface conditions, the ceilings and partitions may be studied for their interaction with each other in their Dynamic Environments. The Dynamic Environment for any system in this chapter is assumed to be one in which systems will be subjected to significant interstory relative displacements, in addition to shear, bending, and axial forces due to accelerations. Typically the Dynamic Environment for ceiling systems will include the upper floor of the Dynamic Structure, adjacent partitions, and mechanical, plumbing, and lighting systems. The Dynamic Environment for partitions will include the lower floor of the Dynamic Structure, adjacent ceiling systems, and any other systems that may be adjacent to and affect the response of the partitions. For simplicity of analysis in this chapter, only the interaction of ceiling systems and partitions is studied in detail.

All of a building's components acting together determine the building's response as a whole; the nature of this response varies from location to location within the building. The building response at any one particular location is the Dynamic Environment for the components in that location, and components and systems need only be designed to accommodate the vibrational and relative displacement effects of their own particular Dynamic Environments. Vibrational effects include acceleration and frequency of vibration, and result in the shear, bending, and axial forces that a system must sustain. Systems and their connections must be designed to undergo a certain level of acceleration with little or no damage. In order for a component to sustain accelerations it must not only be designed for strength but also for stability. No matter how strong a component is, it cannot sustain forces unless it remains stable. Relative displacement effects require that component and interface design allows for displacement in certain directions relative to other components. Connections that allow for relative displacements in certain directions do not provide stability in those directions. Because components must be stable in order to sustain accelerations, and because they must allow for relative displacements, the design of groups of systems and their interfaces must provide for both the stability and the relative displacements of the combined systems in a particular Dynamic Environment. If both of these requirements are satisfied, then the strength of the systems and/or their connections to other systems can be designed for the acceleration criteria developed by the structural engineer. In this section both relative displacements and stability are examined for different ceiling systems and for full- and partial-height partitions.

The design of groups of systems must provide for both the stability and the relative displacements of the combined systems in a particular Dynamic Environment.

Relative displacements in the horizontal direction are typically caused by interstory relative displacements or by vibration of components that are cantilevered from their supports, such as partial height partitions not attached to a ceiling system. Interstory relative displacements are commonly calculated in the structural analysis of a building and design criteria are developed by the structural engineer. Relative displacements in the vertical direction may be caused by simultaneous horizontal displacements, or, in the case of very flexible buildings, by differences in

relative displacements in the vertical direction the amount of deflection of the beams in two consecutive floors. The actual extent of vertical relative displacements that may occur due to seismic forces is not well documented, but in "flexible" buildings care should be taken to design for vertical relative displacements when systems or combinations of systems span from floor to floor. Criteria for vertical displacements caused by simultaneous horizontal displacements can be estimated based upon the criteria for horizontal displacements. Criteria for vertical relative displacements caused by increased or out-of-phase floor deflections can be calculated as a percentage of the requirements for dead and live load deflections.

The Design of Ceiling Systems That Have No Adjacent Partitions

In some cases, a building may have large areas of floor space with ceiling systems and no adjacent interior partitions. This situation is typical of "office landscaping" schemes where partitions are free-standing and of very low-height, and in layouts where there are no partitions at all. In such cases ceilings should be one of the systems discussed in this chapter under "Ceiling Systems" (all of these have vertical compression members), precautions should be taken to prevent ceiling tiles or panels from being dislodged in response to vertical motions, and lateral stability must be provided if the system is unbraced. Horizontal stability for unbraced ceiling systems may sometimes be provided by attaching the ceiling to the columns so that the ceiling system moves in-phase with the Dynamic Structure. Also, an unbraced ceiling system may sometimes be stabilized by attaching it to the exterior enclosure wall, but the exterior wall must also be designed to move in-phase with the Dynamic Structure.

Before proceeding with the analysis of combined ceiling systems and partitions, a review of the assumptions regarding the physical properties of ceiling systems and partitions may be helpful:

- Unbraced ceiling systems, both with rigid and flexible ceiling planes, are assumed to be unstable and require bracing by some other adjacent component or system at intervals frequent enough to prevent them from hammering against or pulling apart from other systems.

- A "restrictive support" along the ceiling plane is one at which vertical motions must not be transmitted from a partition (or some other system) to the ceiling at this point; motions may be transmitted to a "nonrestrictive support," but they do not have to be.
- Partitions are assumed to be stable in the axis parallel to their facings and unstable in the axis perpendicular to their facings.
- Partitions can tolerate very little interstory relative displacement in the axis parallel to their facing.
- Partitions can tolerate a fairly significant amount of interstory relative displacement in the axis perpendicular to their facing, but stability must be provided by some adjacent system.

Partitions Combined with Generic Ceiling Systems

Depending upon whether partitions are full or partial height and whether they are combined with a given ceiling system in one or two axes, the requirements for the interaction of the two systems will be different. Ceiling systems and partitions cannot be analyzed separately and combined; the stability of the two systems is interdependent as is their ability to respond to interstory relative displacements. Thus, ceiling systems and partitions are analyzed in the following sections according to their most typical combinations in buildings:

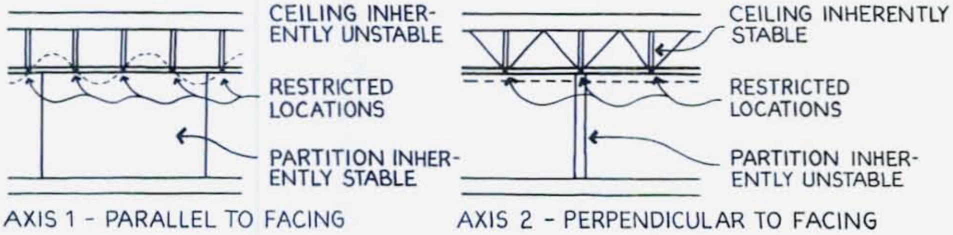
- A partial-height partition in one axis combined with different ceiling systems;
- A full-height partition in one axis combined with different ceiling systems;
- Partial-height partitions in two perpendicular axes combined with different ceiling systems;
- Full-height partitions in one or two axes with no suspended ceiling system (attached to the upper floor);
- Full-height partitions in two perpendicular axes combined with different ceiling systems;
- Full-height partition in one axis, partial-height partition in the other axis, with different ceiling systems.

Partial-Height Partition in One Axis Combined with Different Ceiling Systems

In some cases a partition may either stand free of other partitions or it may be so infrequently braced by intersecting partitions that portions of it act as if they were not affected by those intersecting partitions.

In some cases a partition may either stand free of other partitions or it may be so infrequently braced by intersecting partitions that portions of it act as if they were not affected by those intersecting partitions. In these instances the partition's stability in the axis perpendicular to its facing must be provided by the ceiling system (or some adjacent system). In addition, the partition must, of course, be capable of accommodating interstory relative displacements.

A. PARTITION IN ONE AXIS COMBINED WITH CEILING SYSTEM:



B. REQUIRED INTERFACE CONDITIONS:

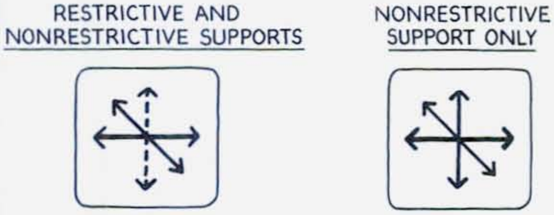
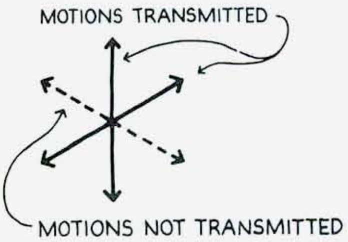


FIGURE 4-28. ANALYSIS OF A PARTIAL-HEIGHT PARTITION IN ONE AXIS COMBINED WITH AN UNBRACED FLEXIBLE/BRACED RIGID CEILING SYSTEM TO DETERMINE INTERFACE REQUIREMENTS.

An analysis of a partial-height partition in one axis combined with a ceiling system can be made as demonstrated by Figure 4-28a. In Axis One (parallel to the facing of the partition) the partition is inherently stable, but the ceiling is not. Hence, in this direction, the two systems must be connected to provide stability for the ceiling, and motions will be transmitted between the two systems. In this direction the partition will dominate the response of the flexible unbraced ceiling (Figure 4-27). The ceiling system will provide the necessary flexibility to accommodate interstory relative displacements.

In Axis Two (perpendicular to the facing of the partition) the partition is inherently unstable, but the ceiling is inherently stable because it is braced. In this direction the two systems must be connected to provide stability for the partition. Because the partitions are "flexible" in this direction, and the ceiling is a rigid braced system, the two systems will affect each other's response significantly: they will be mutually interactive (Figure 4-27). The "significant" role of the ceiling system is necessary for it to be capable of adequately bracing the partition for reasonable levels of design accelerations. The inherent flexibility of the partition in this direction must accommodate any interstory relative displacement.



At restricted locations vertical motions must not be transmitted; vertical motions may be transmitted at nonrestricted locations, but do not have to be transmitted. The result of the above analysis is the interface conditions for restricted and nonrestricted locations shown in Figure 4-28b. A solid arrow indicates that motions are transmitted; a dotted arrow indicates that motions are not transmitted. Figure 4-31 summarizes similar analyses for ceiling and partition types discussed in this chapter in their different combinations of one partial height partition plus a ceiling system.

Full-Height Partition in One Axis Combined with Different Ceiling Systems

In the analysis of full-height partitions, one must simultaneously consider both the interface condition between the top of the partition and the DynS, and between the ceiling edge and the side of the partition.

An analysis of a full-height partition in one axis combined with a ceiling system may be made in a manner similar to the preceding one for a partial-height partition. The analysis for full-height partitions is slightly more complex because one must simultaneously consider both the interface conditions between the top of the partition and the upper floor of the Dynamic Structure, and the interface condition between the ceiling edge and the side of the partition.

In Figure 4-29a a full-height partition has an interface with an unbraced flexible/unbraced rigid ceiling system. In Axis One the ceiling plane is inherently unstable in the horizontal direction and must be stabilized by a connection to the partition, which is stable in this axis. The partition cannot be attached to the upper floor in this direction; the partition will be stable in this axis, and interstory relative displacements may be accommodated by an appropriate interface detail.

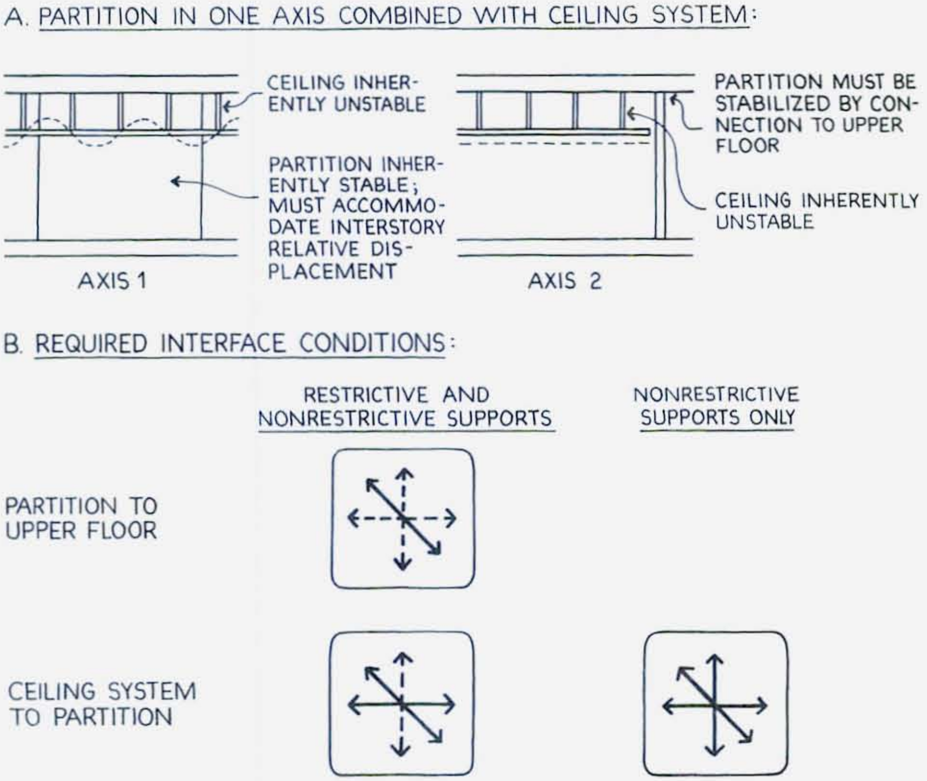


FIGURE 4-29. ANALYSIS OF A FULL-HEIGHT PARTITION IN ONE AXIS COMBINED WITH AN UNBRACED FLEXIBLE/UNBRACED RIGID CEILING SYSTEM TO DETERMINE INTERFACE REQUIREMENTS.

In Axis Two both the ceiling and the partition are inherently unstable. The partition can be stabilized by connecting it to the upper floor. The ceiling, in turn, can be stabilized by attaching it to the stabilized partition. The inherently flexible nature of both the ceiling system and the partition in its transverse axis will accommodate interstory relative displacements.

At restrictive supports along the ceiling plane vertical motions must not be transmitted; vertical motions may be transmitted at nonrestrictive supports, but do not have to be transmitted. The sum of all motion transmittance and nontransmittance requirements is shown in Figure 4-29b. For the partition and ceiling system studied, the partition dominates the response of the ceiling system in both directions. Figure 4-32 summarizes similar analyses for ceiling and partition types discussed in this chapter in their different combinations of one full-height partition plus a ceiling system.

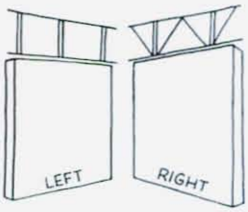
Partial-Height Partitions in Two Axes Combined with Different Ceiling Systems

For simplicity in analysis, two intersecting partitions can first be analyzed for their interaction with each other and the ceiling plane in one axis only. Then the other axis can be analyzed, and the two analyses superimposed.

When two partial-height partitions run perpendicular to each other, their interface with each other and their interfaces with a ceiling system form a unique relationship. The three interfaces must allow the ceiling system and partitions to respond with compatible motions. For simplicity in analysis, two intersecting partitions can first be analyzed for their interaction with each other and the ceiling plane in one axis only. Then the other axis can be independently analyzed and, finally, the two axes combined to produce the interface conditions necessary for compatible ceiling and partition systems. A similar type of analysis can be used for two intersecting full-height partitions and for a partial-height partition intersecting a full-height partition.

The margin illustrates two partial-height partitions and a ceiling system combined within a hypothetical building of flexible response. In Axis 1 the left partition is inherently unstable. The left partition cannot inherently allow for interstory relative displacement in this axis, but the right partition can. The ceiling and partitions will be stable and have compatible responses if the interfaces are designed to have the motion transmittance and nontransmittance characteristics shown in Figure 4-30a. The left partition will brace the right partition in this axis, making the right partition stable. The ceiling system can then be connected to the now stable right partition and is, thus, also stabilized.

In Axis 2 the right partition is inherently stable but the left partition is not. The ceiling system in this axis is braced and, therefore, is inherently stable. Only the left partition can accommodate interstory relative displacements in this axis. The ceiling and partitions will be stable and respond compatibly if their interfaces with each other are designed to have the motion transmittance and nontransmittance characteristics shown in Figure 4-30b. Two alternative groups of interfaces that result in compatible systems are also shown. In both groups the braced ceiling stabilizes the left partition in this axis. In Group 1 the partition and the unbraced ceiling are connected in the horizontal direction and will deflect as a whole in response to interstory relative displacements. In Group 2 the ceiling will respond with the left partition to interstory relative displacements, but the right partition will not respond to motions induced by the ceiling or the left partition. In the vertical direction, connections at restricted locations must prevent motions from being transmitted, as indicated by the dotted arrows. At nonrestrictive locations, motions may be transmitted but do not have to be.



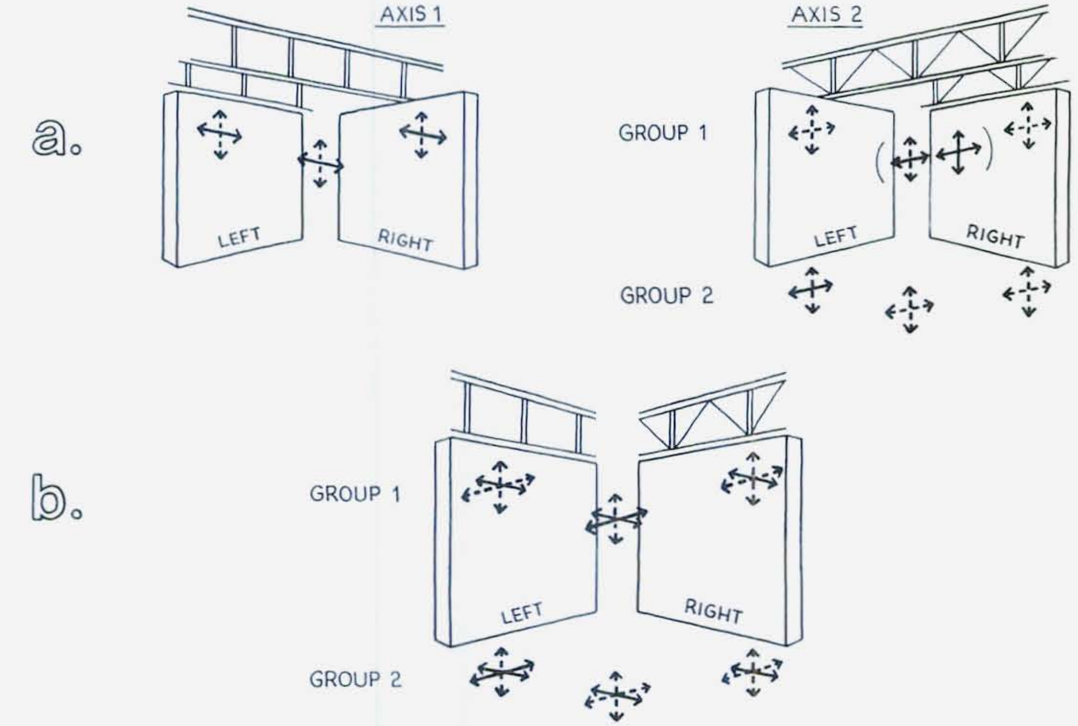


FIGURE 4-30. ANALYSIS OF TWO INTERSECTING PARTIAL-HEIGHT PARTITIONS COMBINED WITH AN UNBRACED/BRACED CEILING SYSTEM TO DETERMINE INTERFACE REQUIREMENTS.

Having analyzed the combined ceiling system and partitions in each axis, one may then superimpose the two axes to produce the requirements for motion transmittance and nontransmittance in all three directions for each interface involved. The only additional requirement for superimposition is that the requirement for vertical motions at the interface between the two partitions be the same for each of the two axes. The results of the superimposition for this example are shown in Figure 4-30b. Figure 4-33 provides analyses of the various partition and ceiling types in combination for their two axes. These analyses may also be combined by superimposition to provide interface requirements for any given combination of partial height partitions and a ceiling system. Superimposition will yield a total of four different combinations of ceiling systems and partial height partitions.

Full-Height Partitions in Two Axes without Suspended Ceiling System

Full-height partitions in two axes can be designed for the same interface conditions as those of partial height partitions that are combined with rigid-braced/rigid-braced ceiling systems. The only difference is that all locations are restrictive. Thus one may design perpendicular full-height partitions that are not adjacent to a ceiling system by superimposing the rigid-braced ceiling/partition combinations of Figure 4-33 in two axes.

Full-Height Partitions in Two Axes Combined with Different Ceiling Systems

The analysis of full-height partitions is somewhat more complex than that for partial-height partitions because there are five, rather than three, interfaces that must be designed.

Full-height partitions in two axes can be analyzed in the same manner as partial-height partitions. The analyses for each axis for full-height partitions combined with different ceiling systems are shown in Figure 4-34. The analysis of full-height partitions is somewhat more complex than that for partial-height partitions because there are five, rather than three, interfaces involved that must be designed so that both full-height partitions and the ceiling system respond compatibly. The reader may wish to refer back to the sections on single full-height partitions to review their basic characteristics when subjected to shear, axial, and bending forces, and interstory relative displacements. The analyses for full-height partitions shown in Figure 4-34 may be superimposed in a manner similar to

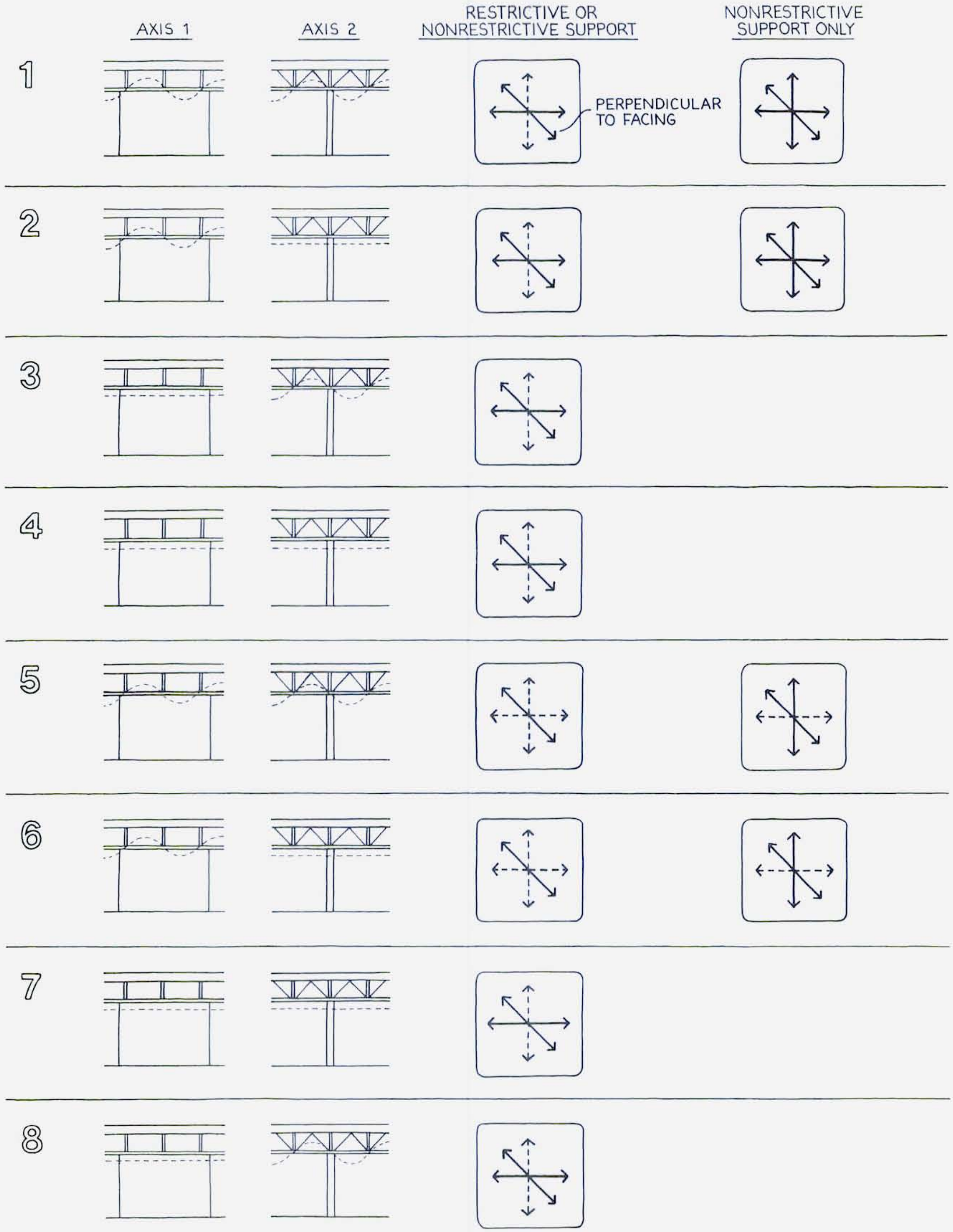


FIGURE 4-31. INTERFACE CONDITIONS FOR A SINGLE PARTIAL-HEIGHT PARTITION AT THE CEILING PLANE.

NOTE 1: AT NONRESTRICTIVE SUPPORTS INTERFACE CONDITION MAY BUT DOES NOT HAVE TO TRANSMIT MOTIONS IN THE VERTICAL DIRECTION: ↕ OR ↕ O.K.

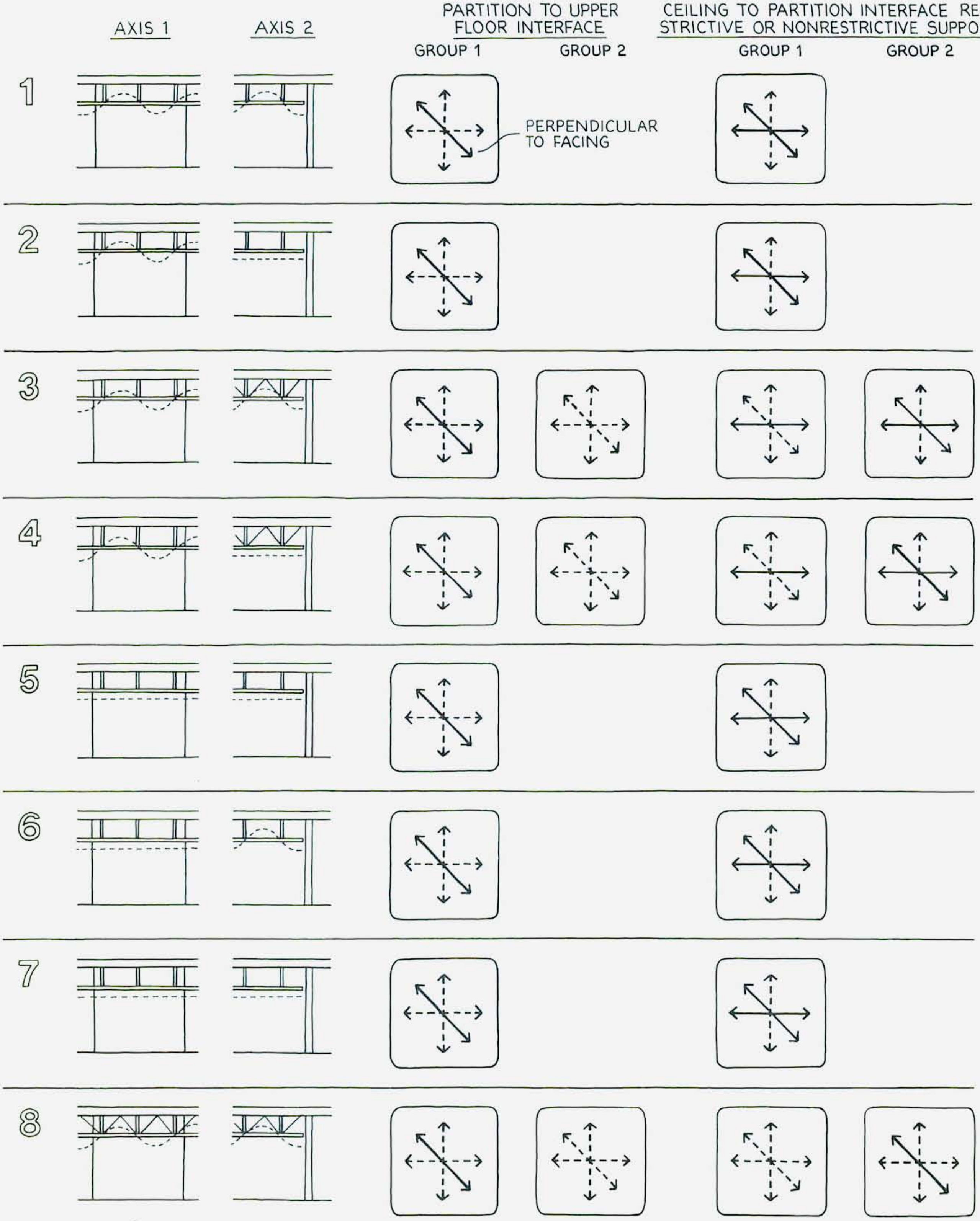
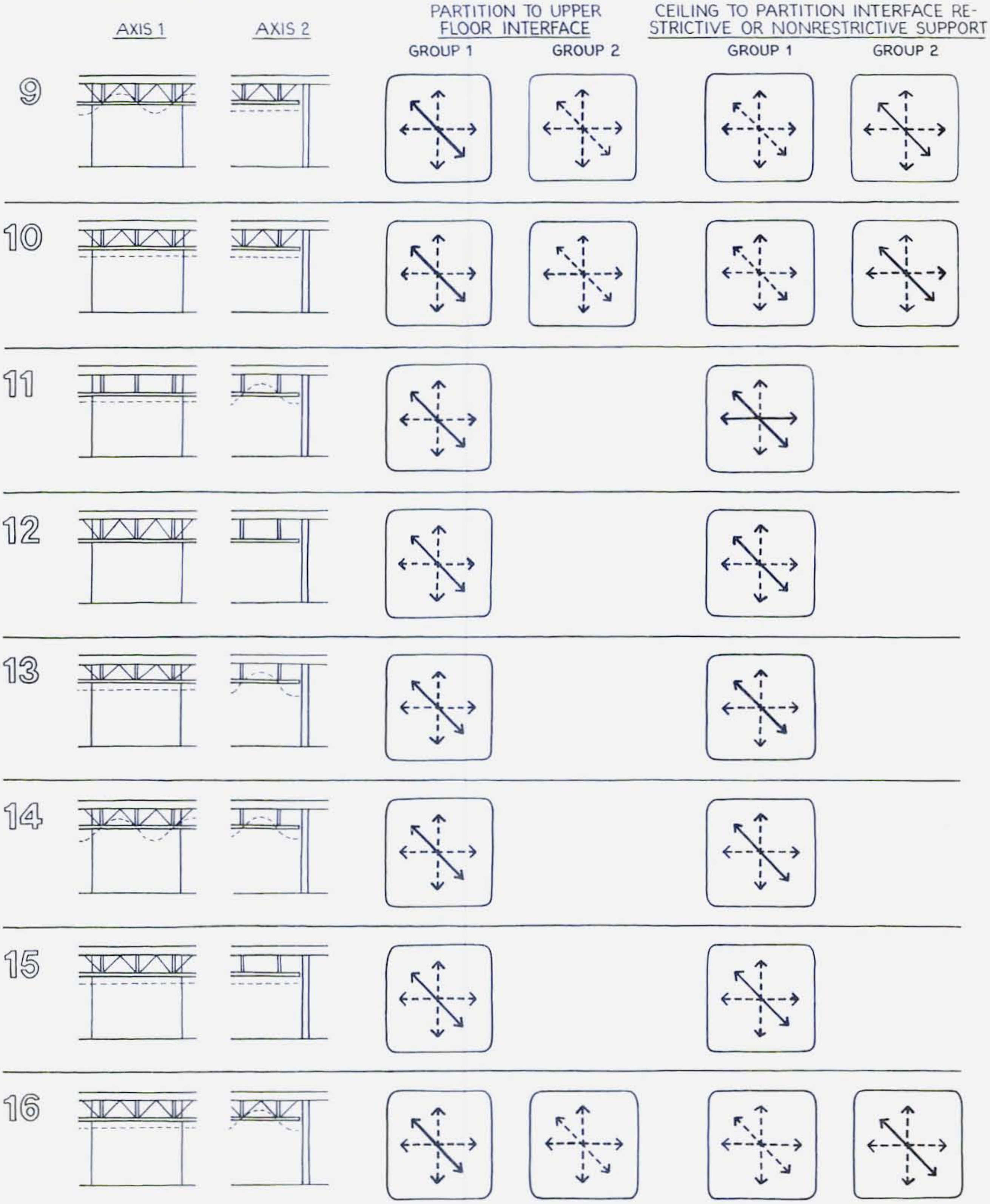


FIGURE 4-32. INTERFACE CONDITIONS FOR A SINGLE FULL-HEIGHT PARTITION AT THE CEILING PLANE.

NOTE 2: AFTER A CERTAIN LENGTH A PARTITION WILL ACT AS IF NOT BRACED BY ANOTHER PARTITION.



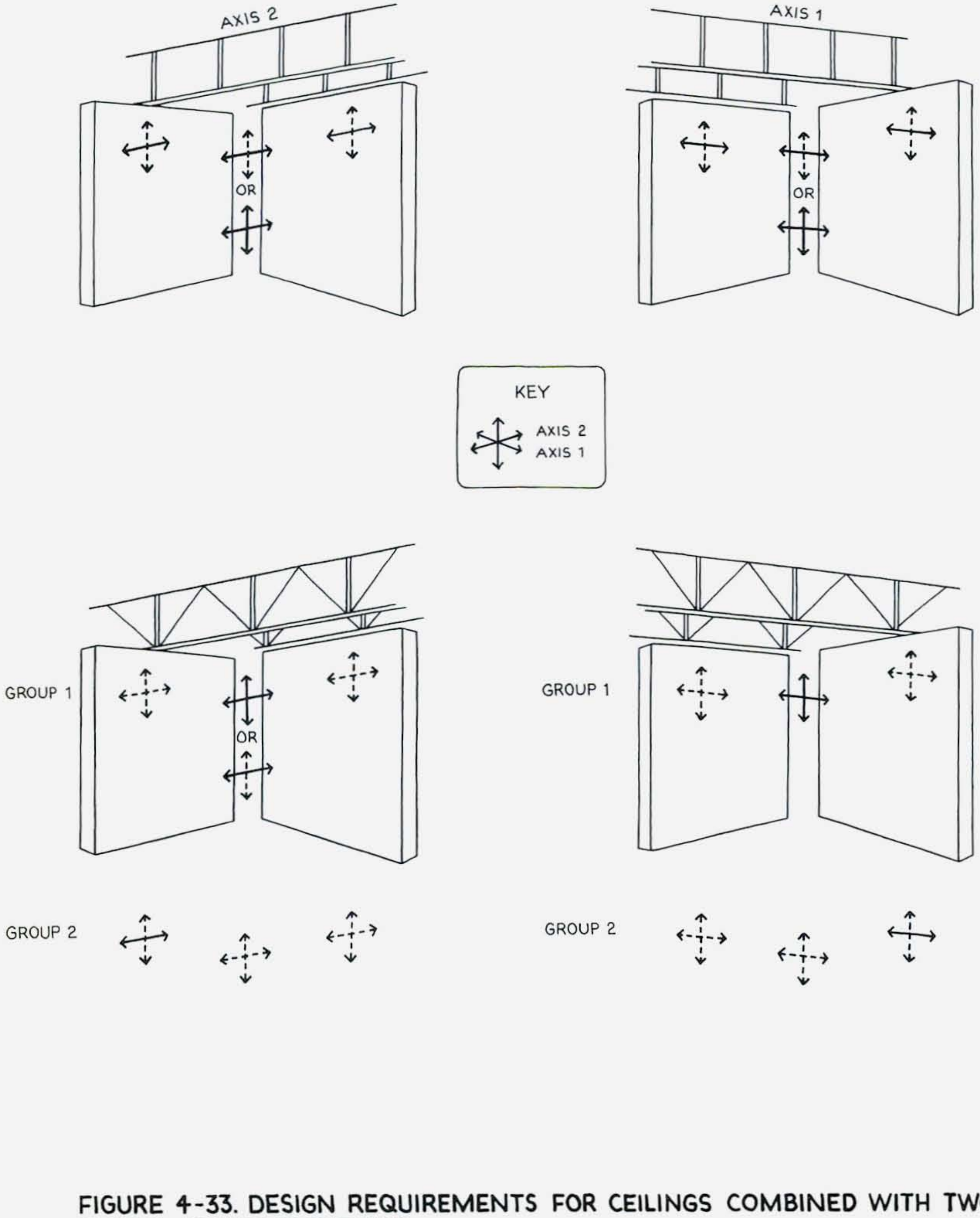


FIGURE 4-33. DESIGN REQUIREMENTS FOR CEILINGS COMBINED WITH TWO PARTIAL-HEIGHT PARTITIONS.

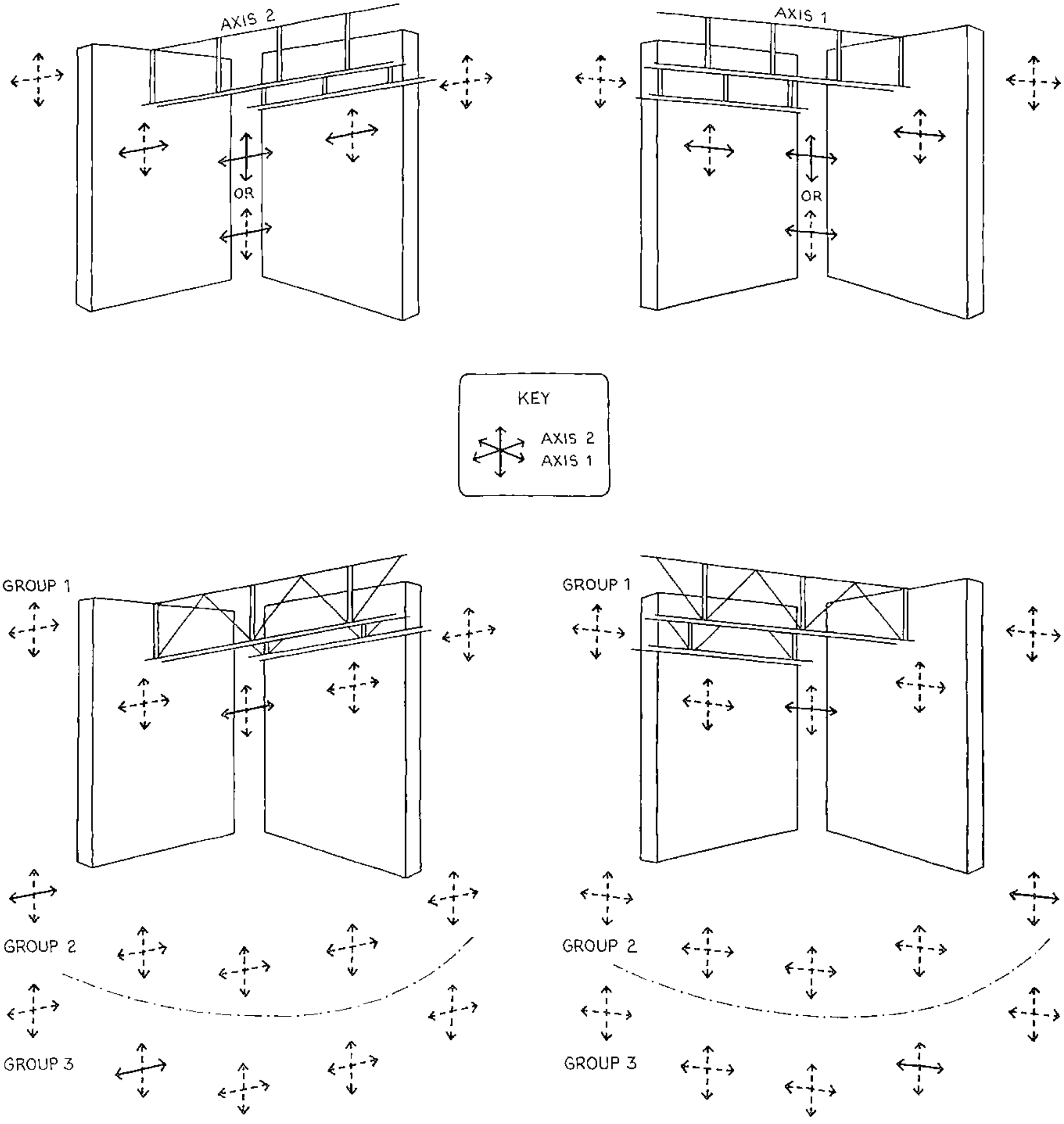


FIGURE 4-34. DESIGN REQUIREMENTS FOR CEILINGS COMBINED WITH TWO FULL-HEIGHT PARTITIONS.

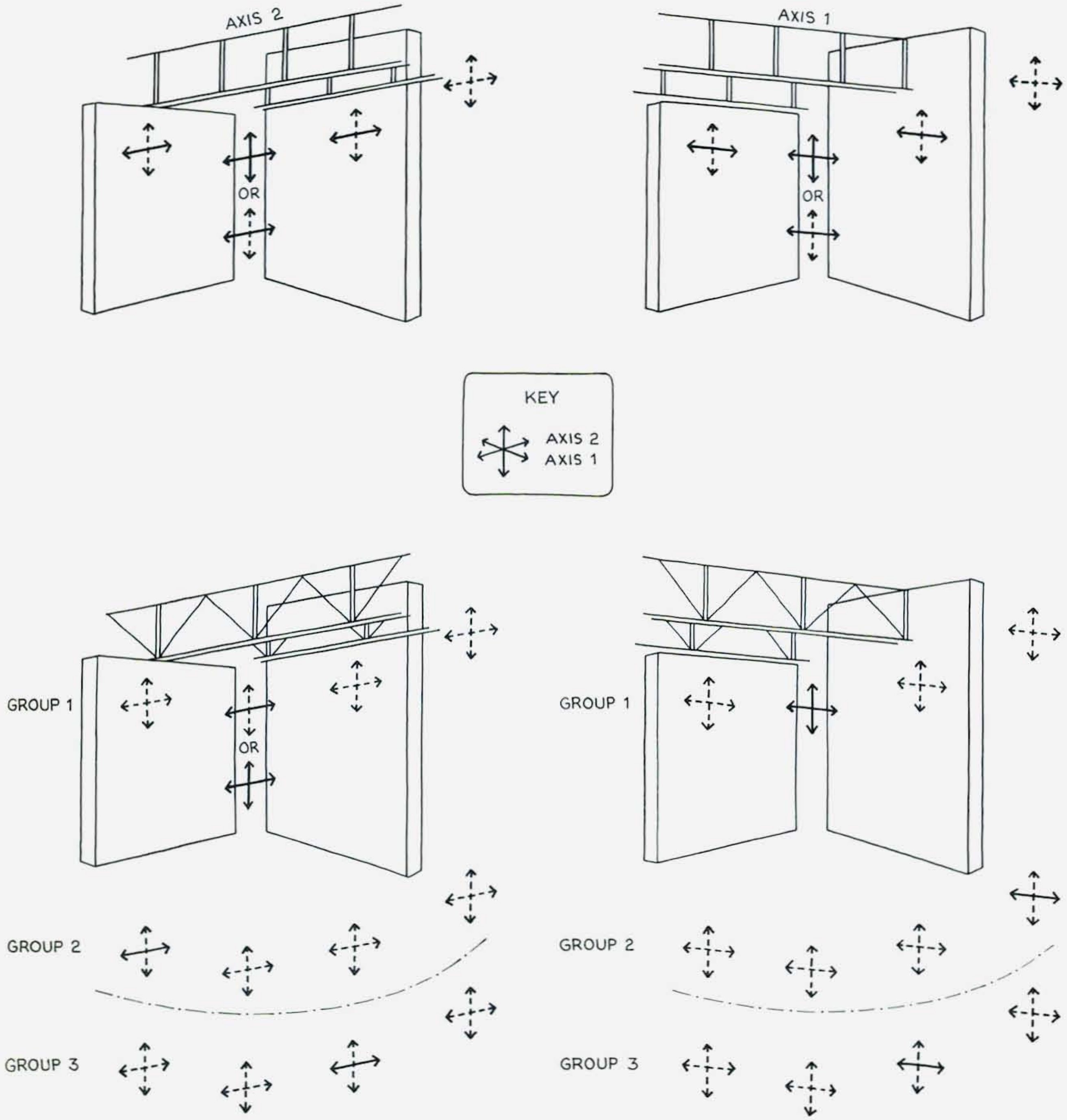


FIGURE 4-35. DESIGN REQUIREMENTS FOR CEILINGS COMBINED WITH ONE PARTIAL-HEIGHT PARTITION AND ONE FULL-HEIGHT PARTITION.

that described in the previous example of partial-height partitions. Such superimposition will yield a total of four different combinations of ceiling systems and full-height partitions.

Partial-Height Partition in One Axis Plus Full-Height Partition in the Other Axis Combined with Different Ceiling Systems

A partial-height partition in one axis plus a full-height partition in the other axis combined with a ceiling system can be analyzed in the same manner as full- or partial-height partitions in both axes. Such an analysis involves four interfaces that must be designed so that both partitions and the ceiling system respond compatibly. The analyses for all combinations of ceilings and partitions are shown in Figure 4-35. Partial-height partitions always appear in Axis 1 and full-height partitions in Axis 2, but the reverse condition can be obtained simply by using the mirror-image of a given diagram. Superimposition of the given combinations of ceiling systems and partitions and their mirror images will yield eight different types of ceiling systems combined with full- and partial-height partitions.

AN ANALYSIS OF CEILING SYSTEMS AND PARTITIONS IN A HYPOTHETICAL BUILDING

Systems and their interfaces will be examined for their potential to damage, and be damaged by other systems, and then alternative methods of designing them to mitigate damage will be proposed.

The analyses and design requirements presented in this chapter will now be applied to ceiling systems and partitions in a section of a hypothetical building. The ceiling systems and partitions, and their interface conditions and details of construction represent typical installations in commercial buildings. However, the use of these different systems and details together in one section of the building is not necessarily typical of actual buildings. Rather, their combined use in this example is for the purpose of studying a range of design and detailing methods. The systems and their interfaces will be examined for their potential to damage, and be damaged by, other systems, and then alternative methods of designing them to mitigate damage will be proposed. This example will demonstrate how one may apply design requirements for interfaces of ceilings and partitions (Figures 4-31, 32, 33, 34, 35) to the design of an integrated section of a building.

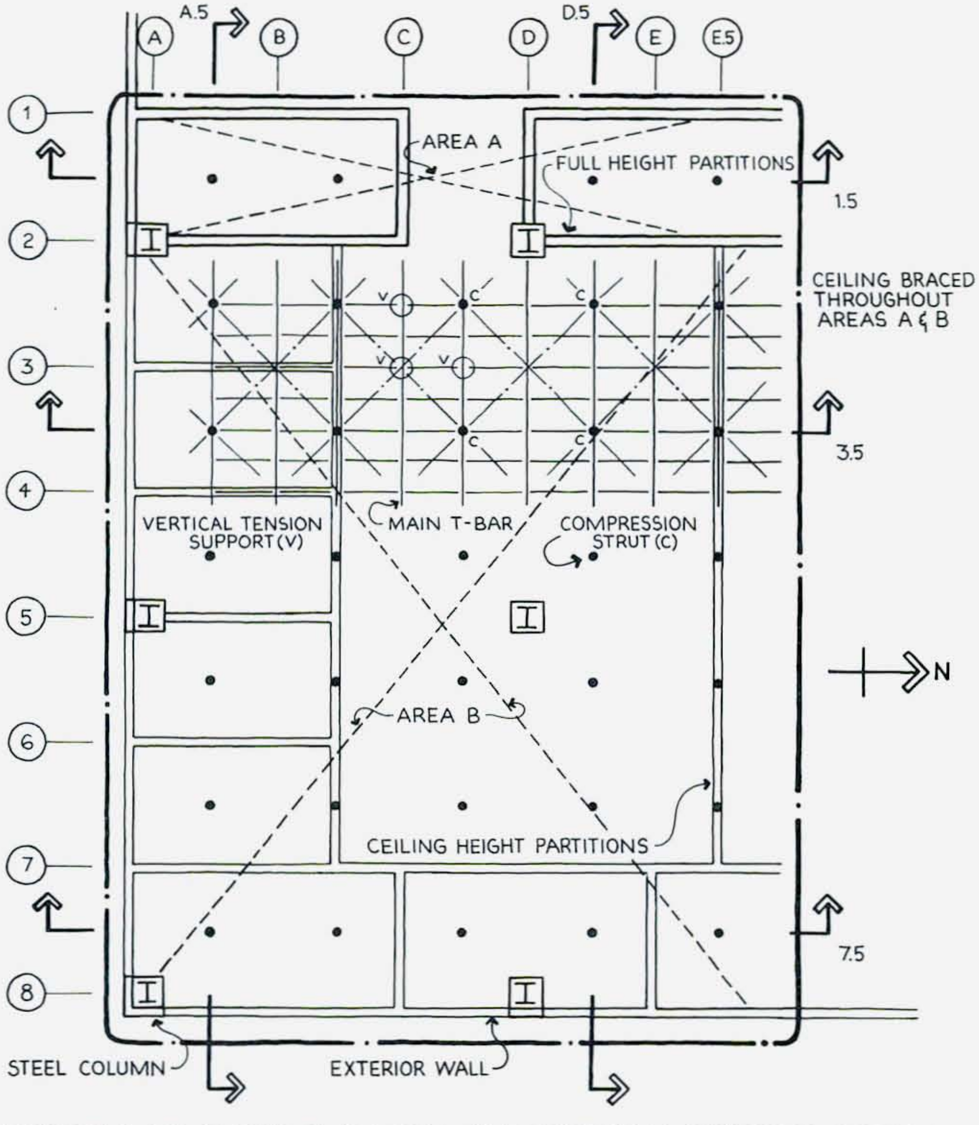


FIGURE 4-36. FLOOR PLAN OF A HYPOTHETICAL BUILDING SECTION.

Conditions Affecting the Dynamic Environments of the Systems Studied

Figures 4-36, 37, and 38 illustrate the hypothetical building section in plan, sections, and typical details. The following conditions have been assumed to affect the Dynamic Environments of the systems and interfaces studied:

- The building's structural frame is ductile steel moment resisting; floors are lightweight concrete on steel deck.

- Interstory relative displacements may be as much as 3/4".
- Vertical relative displacements between floors are ±1/4" from the at-rest position.
- Design live load deflections are 1/2" floor to floor.
- The ceilings and partitions in this section of the building must not significantly modify the response of the building and are assumed to act as Uncoupled Elements.
- The ceiling plane subsystem consists of lightweight lay-in acoustical panels and T-bar frame supports. The main frame supports run in the E-W direction at 4'-0" o.c. The secondary supports run N-S at 2'-0" o.c.
- The ceiling suspension subsystem uses diagonal wires and occasional compression struts (see Figure 4-36 for location of struts).
- Both ceiling-height and full-height partitions are constructed of metal studs at 16" o.c. and gypsum wallboard attached to the studs with metal screws at 7" o.c. at the perimeter, 12" o.c. at intermediate studs. All joints are taped.
- At all locations where two partitions meet, they are connected by metal screws at frequent intervals.
- All partition tracks are attached to the lower floor with power driven nails at frequent intervals.
- The upper track of all full-height partitions is attached to the steel deck with self-tapping screws at frequent intervals. The studs and exterior drywall are not connected to the upper track. There is a 1/2" gap between the upper floor and the tops of the studs and drywall.
- Partitions are separated 3/4" from the columns and exterior curtain wall, and the gap closed with acoustical, closed-cell tape.
- Ceilings are separated 3/4" from the columns and the exterior curtain wall, and the gap air-sealed with flexible closure strips.
- Ceilings are not separated from air registers, sprinkler heads, or light fixtures. Air supply is through flexible ducts extending from the distribution system, which is supported by and braced to the upper floor. Registers

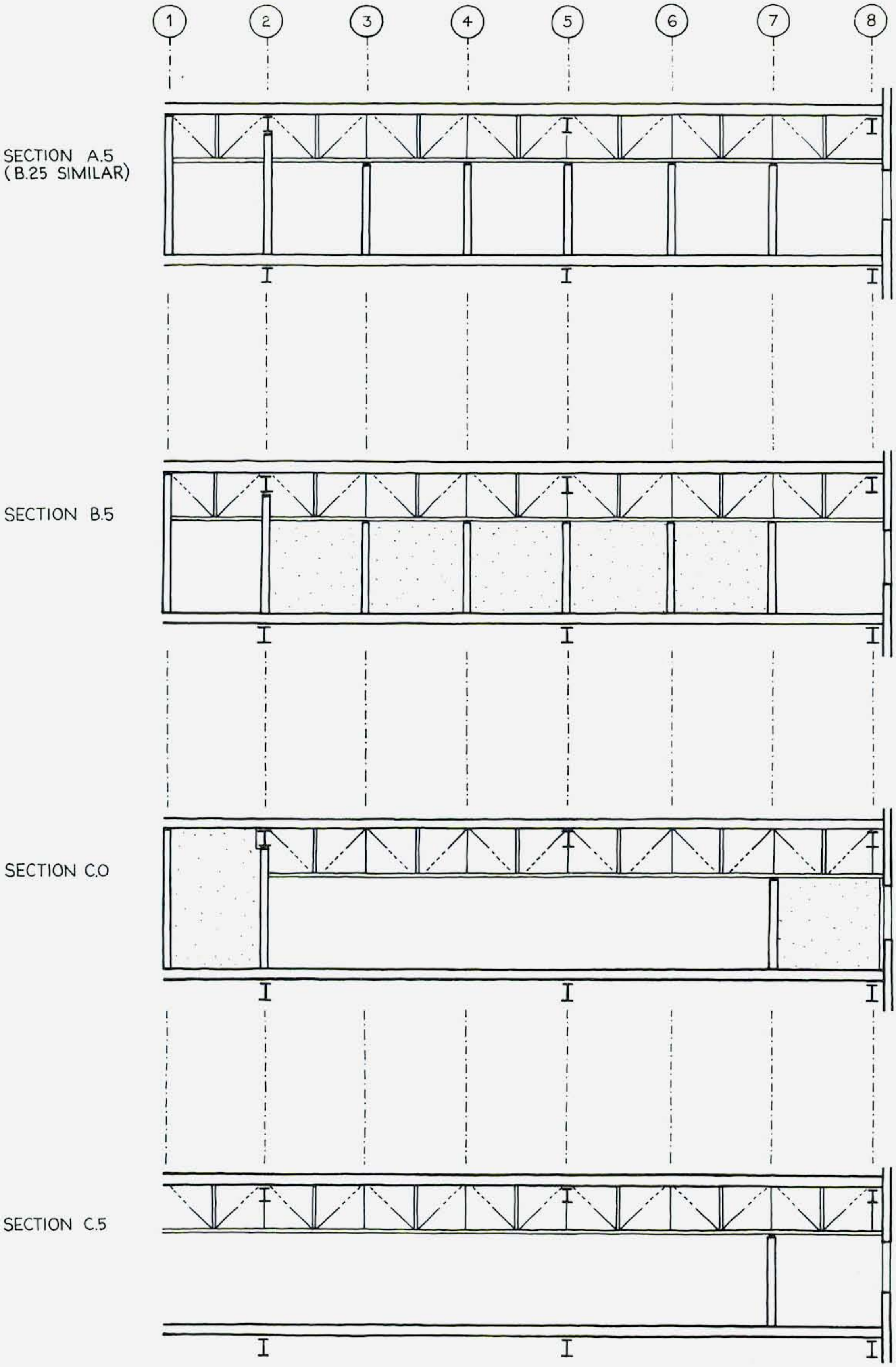
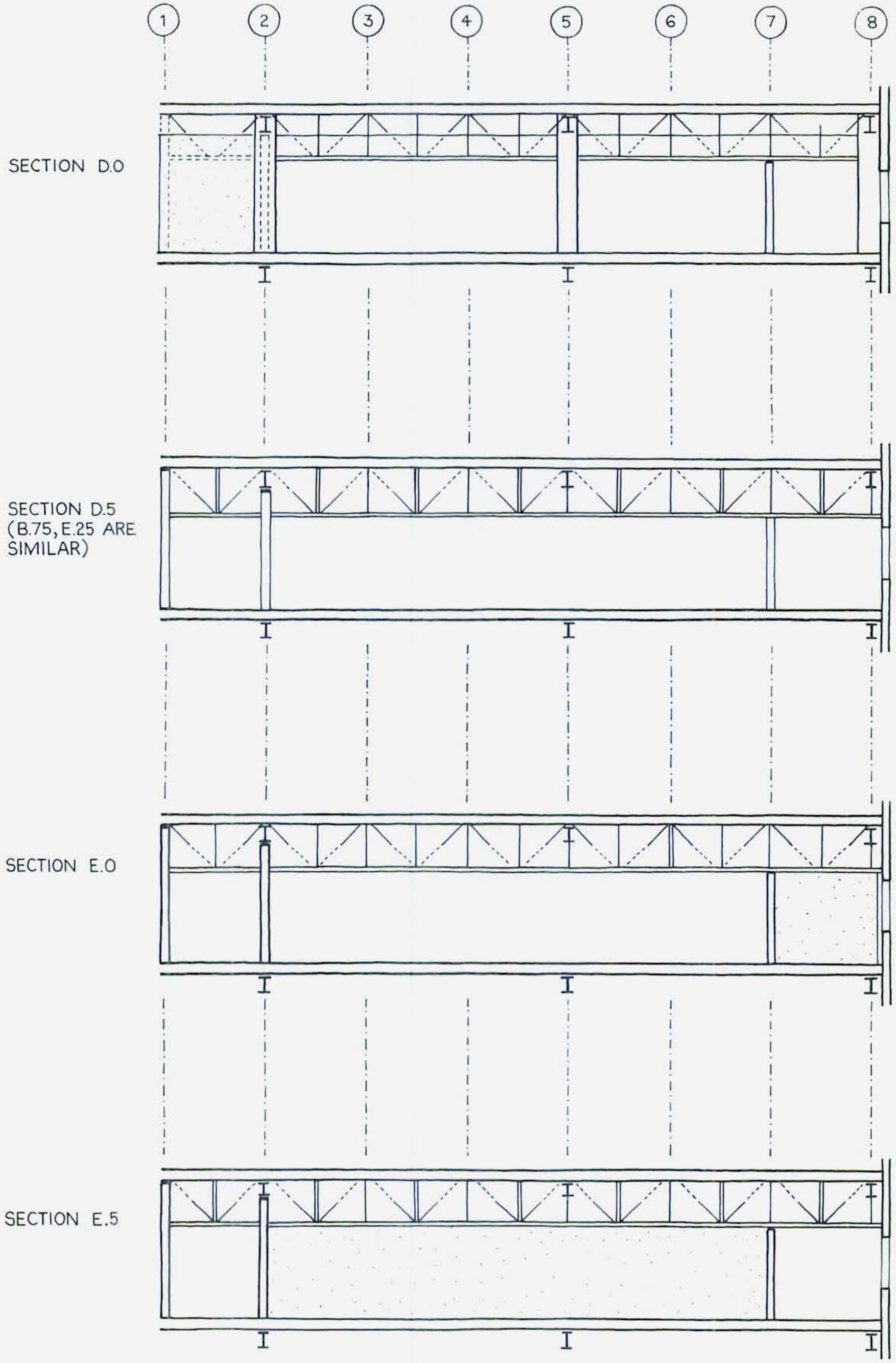


FIGURE 4-37. SECTIONS CORRESPONDING TO HYPOTHETICAL BUILDING PLAN.



1
2
3
4
5
6
7
8
SECTION D.0
SECTION D.5
(B.75, E.25 ARE
SIMILAR)
SECTION E.0
SECTION E.5

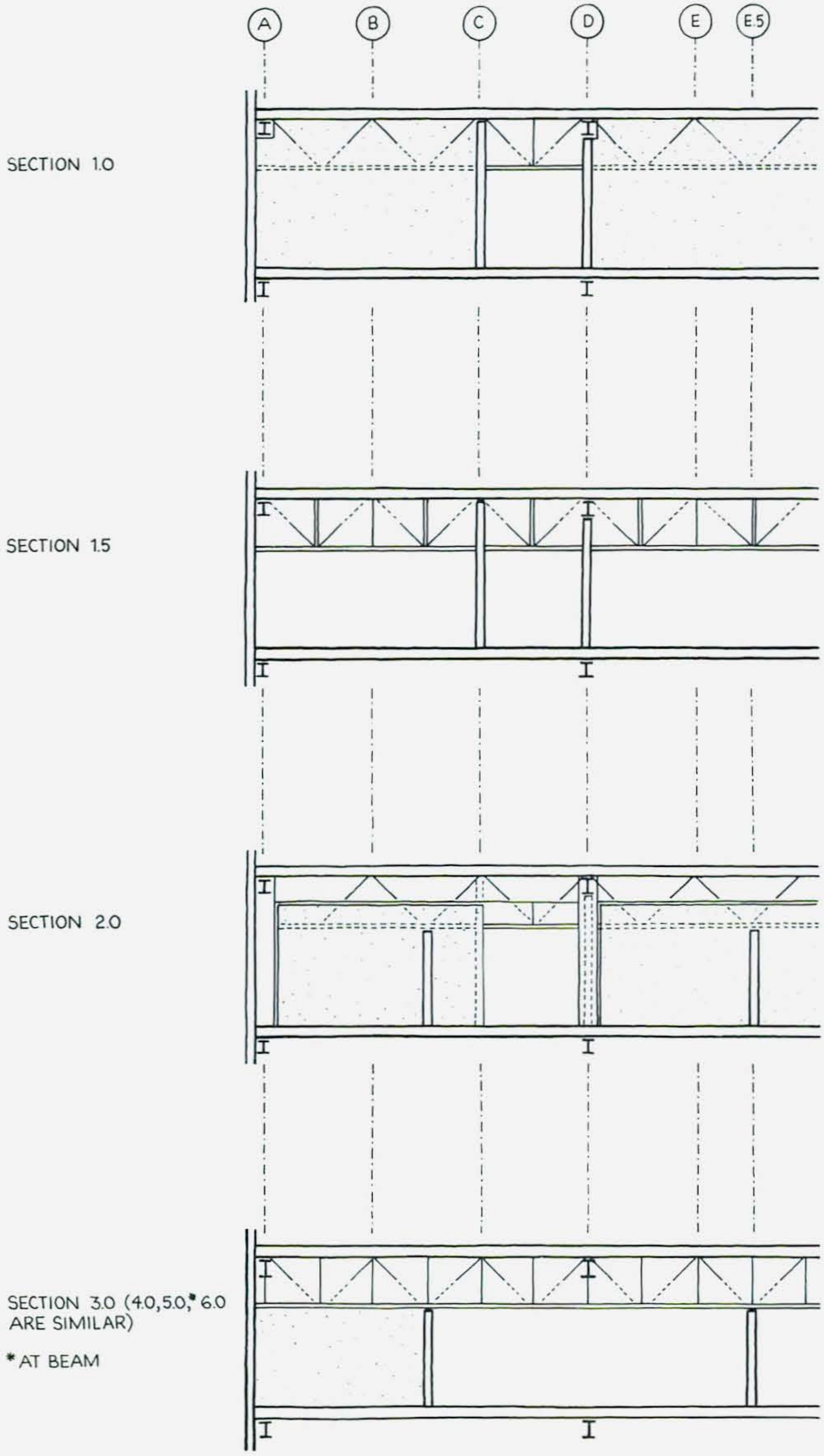
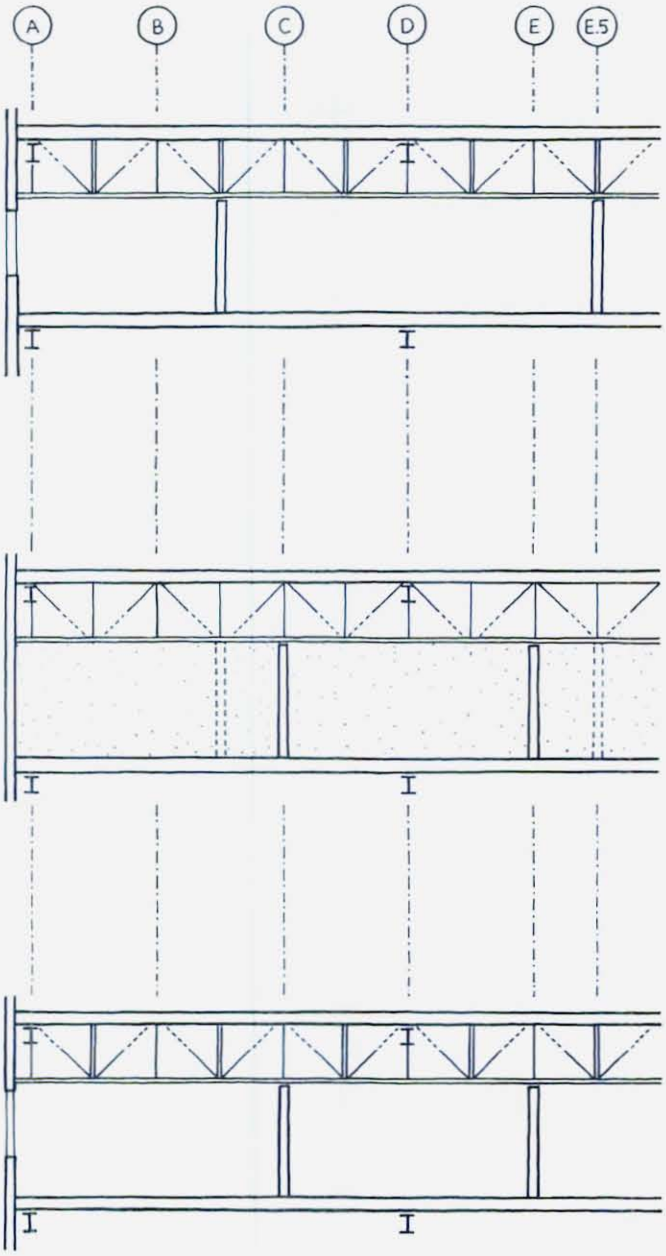


FIGURE 4-37. (CONT'D)



SECTION 3.5 (2.5, 4.5, 5.5, 6.5 ARE SIMILAR)

SECTION 7.0

SECTION 7.5

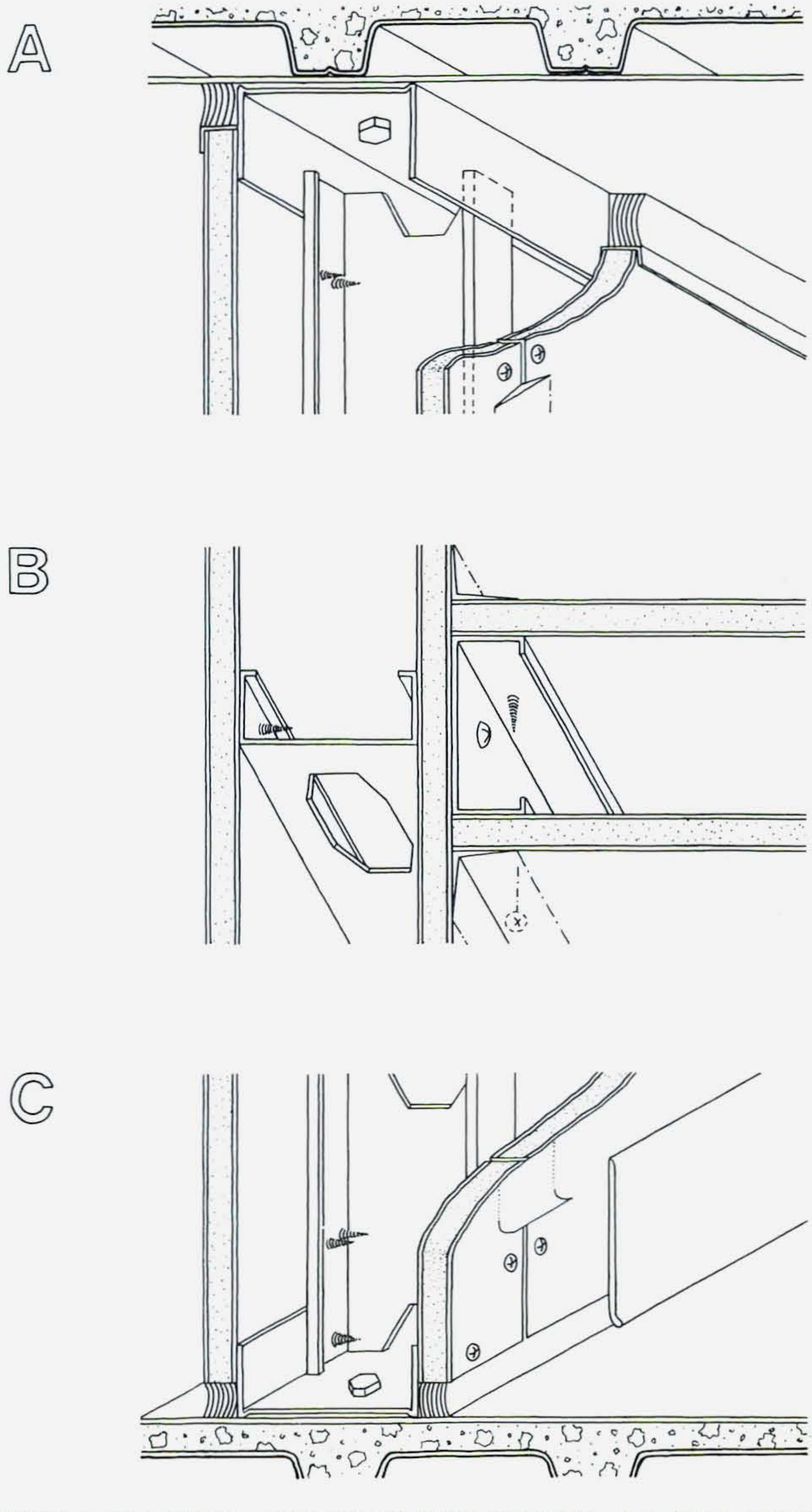
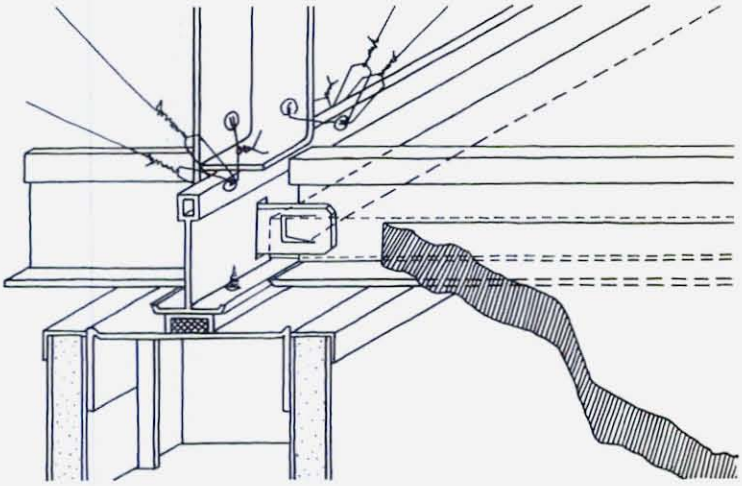
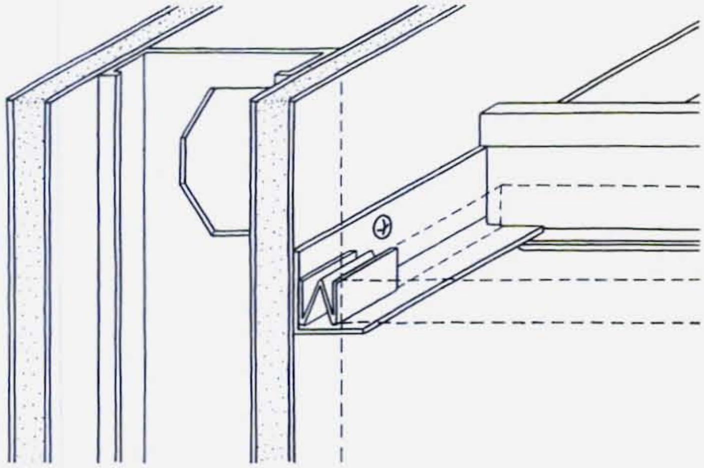


FIGURE 4-38. TYPICAL DETAILS OF HYPOTHETICAL BUILDING SECTION.

D



E



and flexible ducts are supported by the ceiling. Sprinkler mains are supported and braced to the upper floor, but the sprinkler drops are not braced. Light fixtures are supported and braced to the upper floor.

- Ceilings run continuously over the tops of the ceiling-height partitions, with a 1/2" gap separating them. This gap is closed with compressible foam tape. Where partitions and the main frame supports of the ceiling coincide, they are connected with metal screws; a metal spacer channel is inserted to maintain a 1/2" gap.
- Where ceilings meet full-height partitions, the ceiling perimeter is supported by a continuous angle connected to the partition. Spring clips maintain a 1/2" gap between the edge of the ceiling panels and the partitions.

Method for Determining Potential Damage and Design Alternatives

segments

The hypothetical building section will be broken down into "segments" of ceiling systems combined with partitions, which are similar to the typical ones in Figures 4-31 through 4-35. These segments will be studied to determine the potential transmittance and nontransmittance of motions through the affected interfaces during an earthquake. These anticipated responses will be compared to the design requirements for compatible systems shown in Figures 4-31 through 4-35, in order to ascertain whether or not damage can be expected.

The hierarchy of component interaction in Figure 4-27 can be used ... to determine which systems will be most susceptible to damage when their interface conditions make them incompatible with other systems.

The hierarchy of component interaction described in Figure 4-27 can be used not only to identify the type and degree of interaction between systems, but also to determine which system(s) will be most susceptible to damage when their interface conditions make their responses incompatible with responses of other systems. Based on Figure 4-27, a few basic assumptions can be made regarding the potential for damage to ceilings and partitions:

- The Dynamic Structure is capable of damaging braced systems as well as partitions, both in their flexible and in their rigid axes, and is unlikely to be damaged by these systems.
- One partition in its rigid axis is capable of damaging

braced ceilings as well as another partition in its flexible axis; little damage will occur to the first partition as a result of either interaction.

- Partitions in their flexible axis and braced ceilings will be mutually interactive and will damage each other to a relatively equal degree.

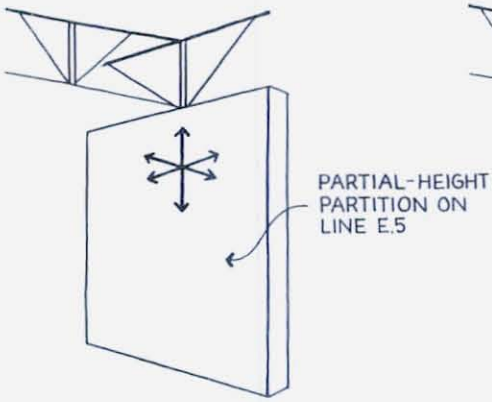


FIGURE 4-39. POTENTIAL MOTION TRANSMITTANCE BETWEEN SYSTEMS IN SEGMENT NO. 1 AS ORIGINALLY DETAILED. SEE DETAILS 4-38 C, D.

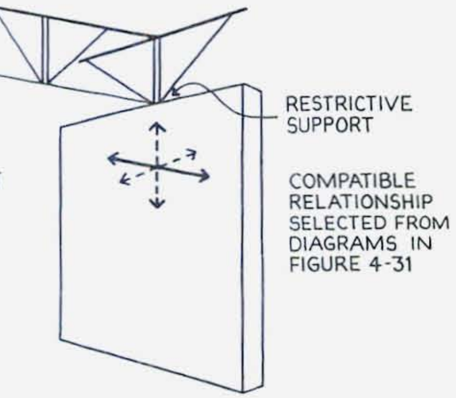


FIGURE 4-40. DESIGN REQUIREMENTS FOR COMPATIBLE RESPONSE OF SYSTEMS IN SEGMENT NO. 1.

ANALYSIS OF SEGMENT NUMBER ONE

Segment No. 1 consists of a portion of the long partial-height partition located on line E.5. Figure 4-39 indicates in which axes motions will be transmitted through the interface of the partition with the ceiling system as detailed in Figure 4-38c,d. Figure 4-40 shows the design requirements based on Figure 4-31 and indicates that only one group of motion patterns is acceptable if the responses of the two systems are to be compatible. Comparison of the anticipated response due to detailing, with the design requirements for compatible response, indicates that the two systems have been detailed to respond incompatibly and damage is likely to occur.

Probable Damage Due to Seismic Motions

A moderate amount of interstory relative displacement (somewhat less than 3/4") may cause the following damage:

- The connections between the top of the partition and the ceiling system may fail.
- Should the above connections withstand the motions imposed upon them, then the ceiling plane frame or the diagonal suspension wire connections may fail.
- If the connections between the systems or the diagonal bracing fail, then the partition will become a vertical cantilever and may suffer damage from stresses due to vibration and/or overturning.

Small vertical relative displacements between floors may cause the following damage:

- The compression members of the ceiling suspension may crush the top track of the partition to some extent.
- The tension members of the suspension system may strip the screw threads of the connections to the partition at restrictive supports.

Design Alternatives for Mitigating Damage

One of the following alternatives could be used to mitigate the anticipated damage:

- The connection between the ceiling system and the partial-height partition could be detailed to transmit only those motions that result in the compatible response of the two systems. Matching the design requirements in Figure 4-40 with the corresponding details in Figure 4-26 will yield one example of the necessary interface detail.
- The ceiling system could be designed to be unbraced in the E-W direction, resulting in a new set of design requirements developed from Figure 4-31. These requirements could be met by choosing an appropriate interface detail from Figure 4-26, or its design equivalent.
- The partition could be stabilized by connecting it directly to the upper floor, either with diagonal bracing or with an extension of the studs to the upper floor. This design alternative results in the partition behaving more like a full-height partition and, hence, would require a different set of design requirements as illustrated by Figure 4-32.

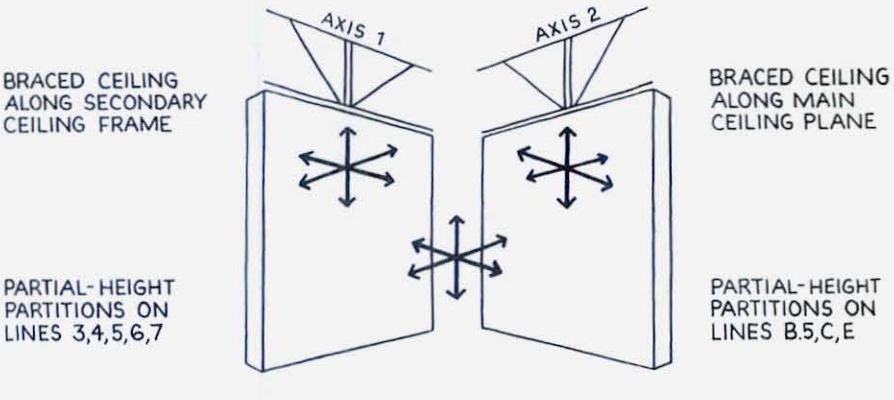


FIGURE 4-41. POTENTIAL MOTION TRANSMITTANCE BETWEEN SYSTEMS IN SEGMENT NO. 2 AS ORIGINALLY DETAILED. SEE DETAILS 4-38B,C,D.

ANALYSIS OF SEGMENT NUMBER TWO

Segment No. 2 consists of two adjacent partial-height partitions and a ceiling system braced in both axes. Figure 4-41 is an idealized representation of the ceiling system, since the diagonals are actually located at 45^{o} angles to the ceiling frame grid, as shown in sections 3.0 and B.5. Figure 4-41 represents the anticipated motions in the axes parallel to the ceiling frame grid. Design requirements for making the given systems compatible are developed from Figure 4-33 and are shown as two alternatives in Figure 4-42. Comparison of the systems as detailed, with the two alternative groups of design requirements, reveals that the systems as designed will respond incompatibly to seismic input motions. The two alternatives in Figure 4-42 indicate that if, in this case, motions are transmitted between partitions, then no motion can be transmitted between the partitions and the ceiling, and vice versa. Based upon the physical properties of each system and the given connection details at each interface, damage is likely to occur.

Probable Damage Due to Seismic Motions

A moderate amount of interstory relative displacement may cause the following damage:

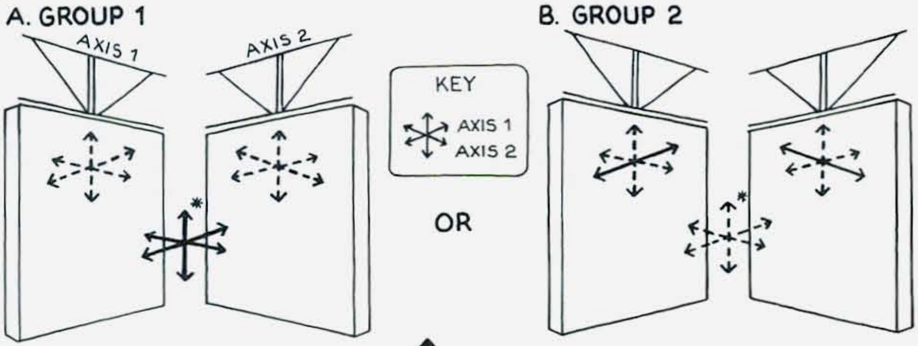
- The connections between the ceiling system and the tops of the partitions may fail. Such failure would cause the two systems to respond in a manner corresponding to the Group 1 design requirements (Figure 4-42a) except at the partition-to-partition interface. As a result, after such failure, the systems would experience less additional damage.

- If the connections do not fail, then the ceiling plane frame or the diagonal suspension wire connections will probably fail.
- The partitions would suffer little or no damage because they will be dominant in their interaction with the ceiling system (Figure 4-27)

Small vertical relative displacements between floors may cause the following damage:

- The compression members of the ceiling suspension may crush the top track of the partition to some extent.
- The tension members of the suspension system may strip the screw threads of the connections to the partition at restrictive supports.

NOTE: GROUPS OF COMPATIBLE RELATIONSHIPS DEVELOPED FROM COMBINATIONS OF DIAGRAMS IN FIGURE 4-33.



* VERTICAL CAN BE ↕ AT NONRESTRICTIVE SUPPORT

FIGURE 4-42. DESIGN REQUIREMENTS FOR COMPATIBLE RESPONSES OF SYSTEMS IN SEGMENT NO. 2.

Design Alternatives for Mitigating Damage

One of the following alternative design strategies would mitigate damage:

- The connections between the ceiling system and the partial-height partitions could be redesigned (for examples see Figure 4-26) so that the system's responses would conform with the design requirements in Figure 4-42a.
- The connections between the ceiling and partition sys-

tems and between the partitions could be redesigned such that the motions transmitted would be the same as in Figure 4-42b. This alternative would probably require some additional reinforcing of the ceiling plane frame since the partitions would be dependent on the ceiling for stability in their flexible axis.

- The ceiling could be redesigned as an unbraced system in both axes. This alternative would have different design requirements from those shown in Figure 4-42. The new requirements could be formulated from those for unbraced ceilings in Figure 4-33.
- The ceiling could be redesigned to be unbraced in one axis and braced in the other, again necessitating new design requirements that could be developed from Figure 4-33.

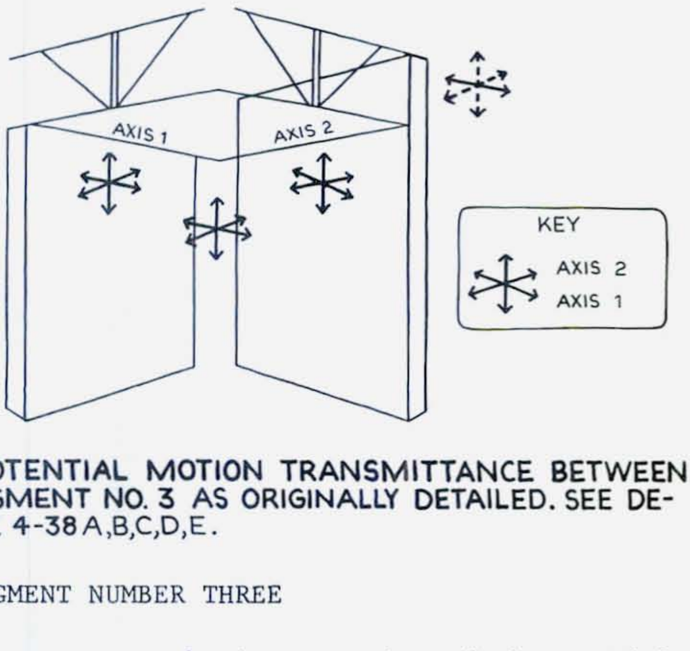


FIGURE 4-43. POTENTIAL MOTION TRANSMITTANCE BETWEEN SYSTEMS IN SEGMENT NO. 3 AS ORIGINALLY DETAILED. SEE DETAILS IN FIGURE 4-38 A,B,C,D,E.

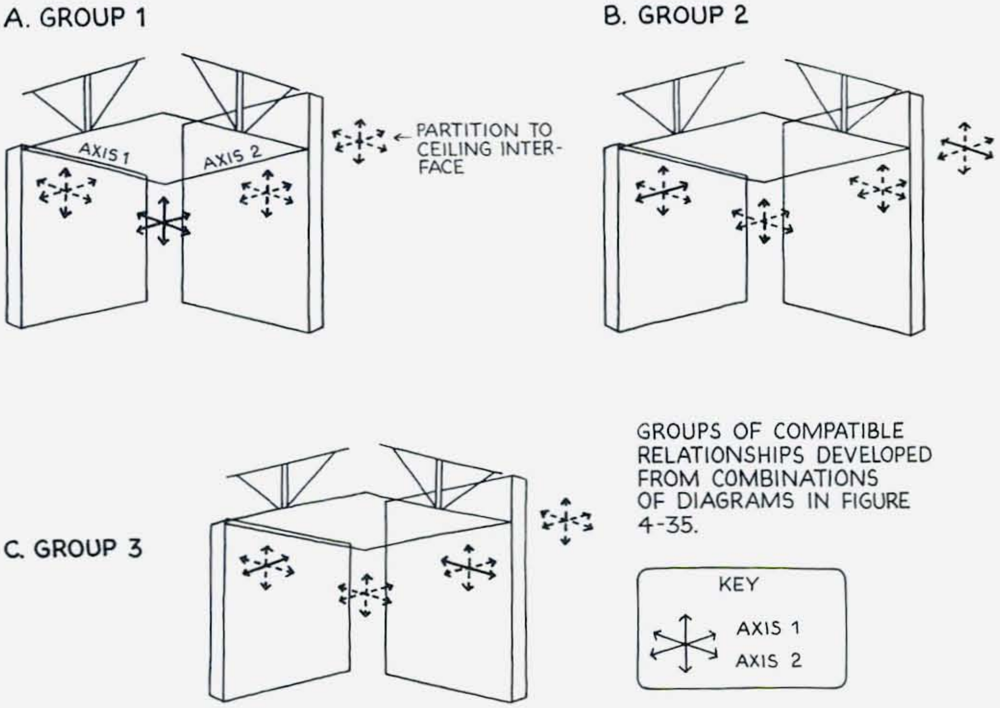
ANALYSIS OF SEGMENT NUMBER THREE

Segment No. 3 represents the intersection of the partial-height partition on line B.5 and the full-height partition on line 2 (see Figure 4-36). Figure 4-43 indicates in which directions motions will be transmitted from one system to the other if the interfaces are detailed as shown in Figure 4-38a,b,c,d,e. Figure 4-44 presents three different groups of interface conditions that would result in the compatible responses of the ceiling and partitions. Comparison of the systems as designed in Figure 4-43, with the design requirements for compatible response in Figure 4-44, indicates that the systems as designed will respond incompatibly.

Probable Damage Due to Seismic Motions

A moderate amount of interstory relative displacement may cause the following damage:

- The connections between the ceiling and the partitions may fail.
- The ceiling's diagonal tension wires and the ceiling plane frame may be overstressed, possibly resulting in some failures of the suspension wire connections, and racking and bending of the ceiling plane frame.
- The connection of the full-height partition to the upper floor may deform and could fail, causing damage to the top edge of the partition.
- If the connection to the full-height partition does not fail, then either the connection between the two partitions will fail, or the surface of the full-height partition will be damaged extensively at or above the ceiling line.


A. GROUP 1

B. GROUP 2

C. GROUP 3

GROUPS OF COMPATIBLE RELATIONSHIPS DEVELOPED FROM COMBINATIONS OF DIAGRAMS IN FIGURE 4-35.

FIGURE 4-44. DESIGN REQUIREMENTS FOR COMPATIBLE RESPONSE OF SYSTEMS IN SEGMENT NO. 3.

Small vertical relative displacements between floors may cause the following damage:

- At the interface between the ceiling and the ceiling-height partition, damage would be similar to that anticipated for Segment No. 1.
- At the interface between the ceiling and the full-height partition, the ceiling would be subjected to bending stresses which would cause the ceiling plane frame to warp. The angle support at the ceiling edge might also be sheared loose or deformed.

Design Alternatives for Mitigating Damage

Like Segment Nos. 1 and 2, interface conditions for Segment No. 3 must be redesigned to result in compatible responses of the systems. This requirement can be accomplished either by meeting the design requirements of Figure 4-44, or by choosing a new ceiling system and designing for its particular interface requirements as defined by Figure 4-35. Because the process of designing compatible systems is similar to that described for Segment Nos. 1 and 2, only a few observations regarding the redesign process for Segment No. 3 are presented:

- The interface between the two partitions as detailed in Figure 4-43 fulfills the Group 1 requirements for compatible response (Figure 4-44a). Hence, if Group 1 requirements are utilized, only the remaining three interfaces need be redesigned.
- The interface between the full-height partition and the upper floor as detailed in Figure 4-43 fulfills the Group 2 requirement for compatible response (Figure 4-44b). The left ceiling-to-partition interface has a compatible response in the flexible axis; hence, the detail at this interface could be partially revised to result in compatible responses in the other two axes as well. Hence, if Group 2 requirements are utilized, only the right ceiling-to-partition and the partition-to-partition interface need be redesigned.
- Two of the four interfaces in Figure 4-44c have compatible responses in some of their axes; the details for these two interfaces could be revised to make them respond compatibly in all three axes. The other two interfaces must be totally redesigned.

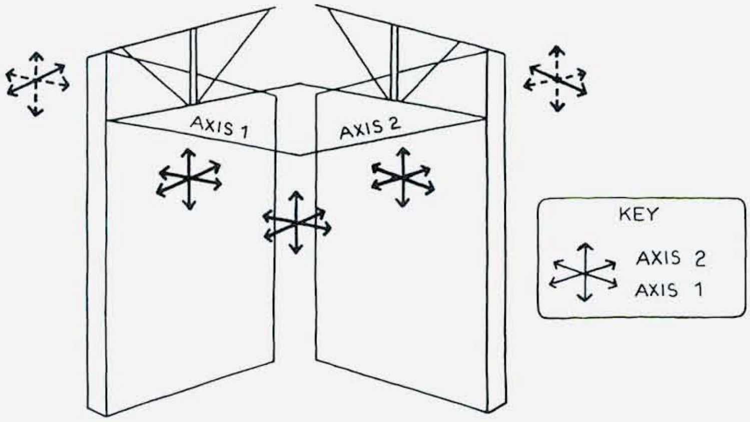


FIGURE 4-45. POTENTIAL MOTION TRANSMITTANCE BETWEEN SYSTEMS IN SEGMENT NO. 4 AS ORIGINALLY DETAILED. SEE DETAILS IN FIGURE 4-38 A,B,C,E.

ANALYSIS OF SEGMENT NUMBER FOUR

Segment No. 4 consists of two intersecting full-height partitions, which have interfaces with the upper floor and the braced ceiling. This condition occurs at the intersection of line C with lines 1 and 2, and at the intersection of line D with line 1. Figure 4-45 illustrates the systems as detailed, and Figure 4-46 lists the five different groups of design requirements for the compatible response of these systems. Because the systems as detailed do not fullfill any one group of design requirements, the systems will respond incompatibly and be subject to damage. This particular segment has the greatest potential for damage because both partitions are full-height and thus must be able to withstand interstory relative displacements.

Probable Damage Due to Seismic Motions

A moderate amount of interstory relative displacement may cause the following damage:

- The ceiling-to-partition connections may fail.
- The diagonal tension wires and the ceiling plane frame may be overstressed, possibly causing some failure of the suspension wire connections and racking and bending of the ceiling plane frame.
- The connection of the full-height partitions to the upper floor may deform and could fail, causing damage to the top edges of the partitions.

Large interstory relative displacements may cause, in addition to the damage described above,

- Overstress of the connection between the two partitions, resulting in failure of the connection or extensive damage to the partition.

Small vertical relative displacements between floors may cause the following damage:

- The ceiling might be subjected to bending stresses which would result in racking and warping of the ceiling plane frame and shearing or bending of the angle support at the ceiling edge.

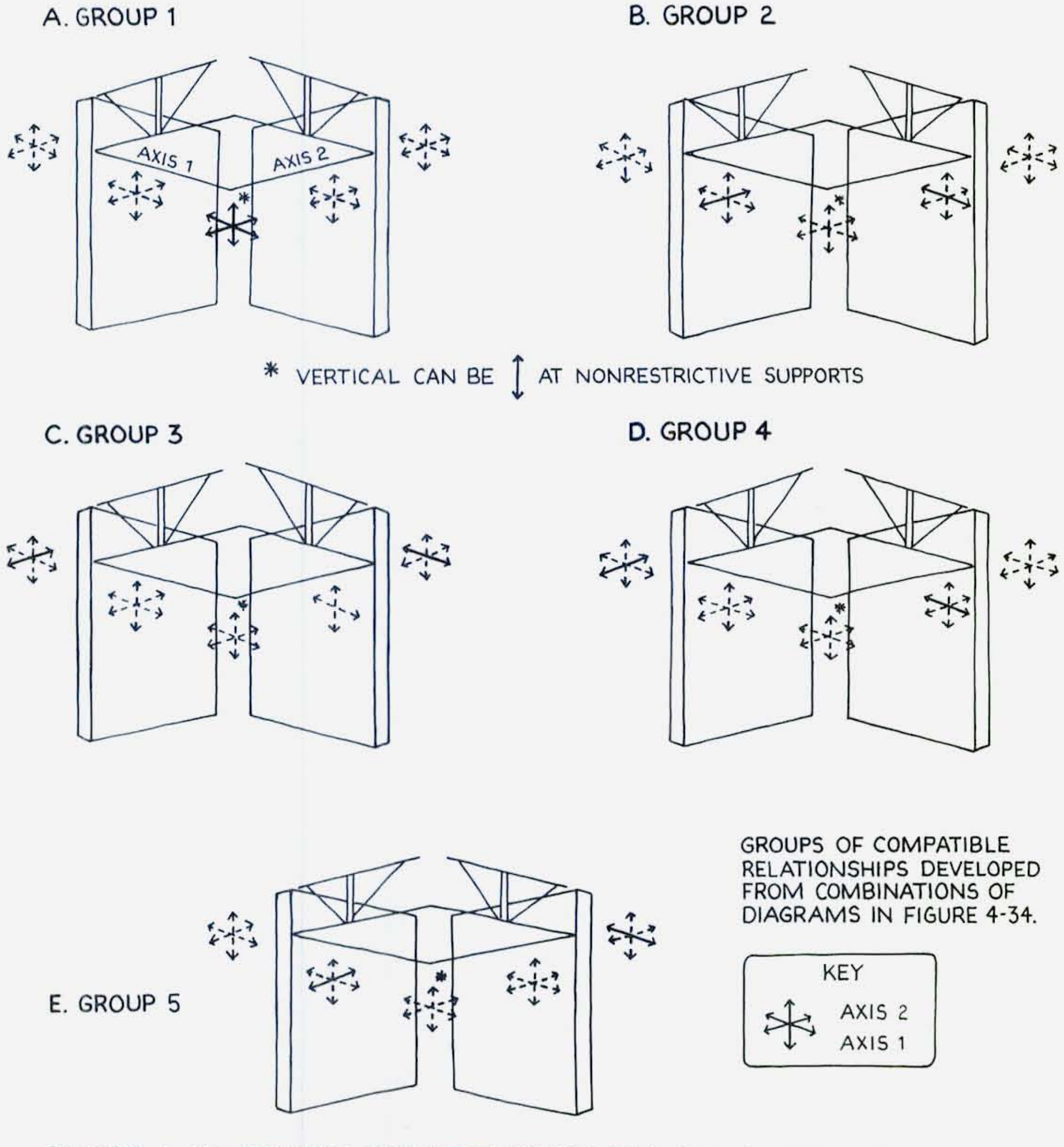


FIGURE 4-46. DESIGN REQUIREMENTS FOR COMPATIBLE RESPONSE IN SEGMENT NO. 4.

Design Alternatives for Mitigating Damage

Damage can be mitigated by methods similar to those discussed for Segment Nos. 1,2, and 3. Either the systems' interfaces can be redesigned to comply with one of the groups of design requirements in Figure 4-46, or new system types can be chosen and a new set of compatible interfaces designed for them.

DESIGNING TO PREVENT CONFLICTING MOTIONS FROM BEING INDUCED WITHIN AN INDIVIDUAL SYSTEM

Each building system or component has its own Dynamic Environment, which includes accelerations and displacements induced through the system's interfaces with other systems or components. Designing the interaction of different systems for compatible responses as discussed in the previous sections is a major step towards designing systems in a building to withstand input motions. However, equally important, a system's different interfaces with other systems must not be designed so that they induce conflicting motions within that system. In other words, the response of a system at one end must not be so different from its response at the other end that stresses are induced. For example, a partition must be designed to move in the same manner at one end as it does at the other. Hence, all of its interface conditions with other systems must allow the same response patterns or the partition must be divided into two (or more) systems by means of a transition interface that will prevent the two (or more) different sections of the partition from influencing each other. Such a transition interface is similar to a seismic expansion joint between different sections of a large building. The simplest way of achieving compatible response within a system is to design all of the similar interfaces with a particular system to be the same. For example, if the interfaces at lines B5 and 4 are designed for the requirements in Figure 4-46a, then the interfaces at line B.5 and lines 3, 5, 6, and 7 should either meet the same requirements or allow the partition that has the interfaces with the other partitions to respond with the same motions at each interface. Otherwise the partition will be pulled apart. The most advisable design procedure in designing a section of a building that has many systems is to choose the fewest different types of systems and then utilize as few different interface conditions as possible.

SUMMARY

The analyses and examples presented in this chapter resulted in some basic observations on the design of ceiling systems, partitions, and other interior systems:

1) In relatively rigid buildings the best design strategy appears to be that of bracing partitions and ceiling systems. Since interstory relative displacements in such buildings will be comparatively small, the interfaces between systems probably do not need to provide for relative displacements.

2) In relatively flexible structures there are alternative means of designing interfaces for relative displacements between systems and meeting the general requirements of the systems themselves:

   - Suspended ceiling systems must incorporate some suspension subsystem components that carry forces in compression as well as tension. Such components must be located at intervals frequent enough to minimize bending and racking of the ceiling plane.
   - Suspended ceiling systems must be stabilized by bracing to the upper floor with diagonal tension wires, or by bracing provided by other systems such as partitions, columns, enclosure systems, and so forth, in order to prevent the ceiling system from responding with uncontrolled patterns of horizontal motions.
   - Partitions must be designed to allow for vertical relative displacements between the upper and lower floor of the Dynamic Structure.
   - Partitions must be stabilized in their flexible axis by the upper floor, a braced ceiling system, or another partition. However, bracing should be provided

by only one of these systems in addition to the connection to the lower floor in order to avoid introducing conflicting patterns of motions.

- All interface conditions affecting one continuous system should allow that system to respond with the same pattern of motions at each of those interfaces. Otherwise, stresses will be induced and damage will result.
- Systems such as light fixtures, ducts that penetrate other systems, plumbing risers, and so forth, must be designed to be compatible with the selected ceiling and partitions, and their interface conditions. For example, a light fixture that is braced to the upper floor must be isolated from a ceiling system that is stabilized by a partition system, but it may be connected to a braced ceiling system that is stabilized by the upper floor. In the former case the isolation between the ceiling and the light fixture is necessary so that the ceiling will not inadvertently act as a braced ceiling and introduce motions that would conflict with those of the partition-to-ceiling connection. In the latter case, if the light fixture has a rigid conduit or other compression-type member, the connection of the ceiling to the light fixture will improve the ceiling's response by further bracing it.

Appendices

Appendix A: Site and Building Response

EXAMPLE #1: A STUDY OF THE POSSIBLE EFFECTS OF SITE CONDITIONS ON BUILDING RESPONSE

Because of the very limited amount of historical data available, there are no examples that illustrate the effects of site variations on the response of buildings to historical earthquakes. Data does not exist for an ideal comparison between buildings at several different sites with varying material properties, located equal distances from the epicenter of a major earthquake. However, the following example is a qualitative description of the potential influence of site conditions on building response. A 15-story ductile moment-resisting steel frame structure will be studied for the hypothetical effects of three different site conditions on its response.

Site	Distance from Epicenter	N-S component	Length of Record	General Soil Condition
A	5 mi.	S 14° W	20.0 sec.	Fractured rock
B	13 mi.	N-S	20.0 sec.	Medium-deep alluvium
C	26 mi.	N 36° E	24.0 sec.	Shallow alluvium with underlying firm siltstone

Example Building (15 stories)

Lateral bracing	Ductile moment resisting steel frame
Foundation	Spread footings
Axis under review	Longitudinal
Modal Periods	T_1 = 2.91 sec., T_2 = 1.02 sec., T_3 = 0.60 sec.

FIGURE A-1. SITE AND GROUND MOTION DATA FOR BUILDING IN EXAMPLE NO. 1

The first three periods of vibration of the example building are 2.91, 1.02, and 0.60 seconds in the direction of the longitudinal axis. The response of the building will be estimated for the input motions produced by the 1971 San Fernando, California earthquake at three different sites, each having different soil conditions. The input motions for each of the three different sites are based on historical records for those sites during the earthquake. The properties of the sites relevant to this study are shown in Figure A-1. Site A was comprised of fractured rock, Site B of medium-deep alluvium, and Site C of a shallow alluvium with underlying firm siltstone. Response spectra from these three sites are shown in Figure A-2. The three response spectra have all been normalized to the same peak ground acceleration for purposes of comparison. The first several modal periods of vibration of the subject building are superimposed on the spectra. The Site A spectrum is computed from a free-field record, that is, free from the influence of any building structure, while the spectra for sites B and C are computed from records that may be somewhat influenced by the response of the buildings in which they were recorded.

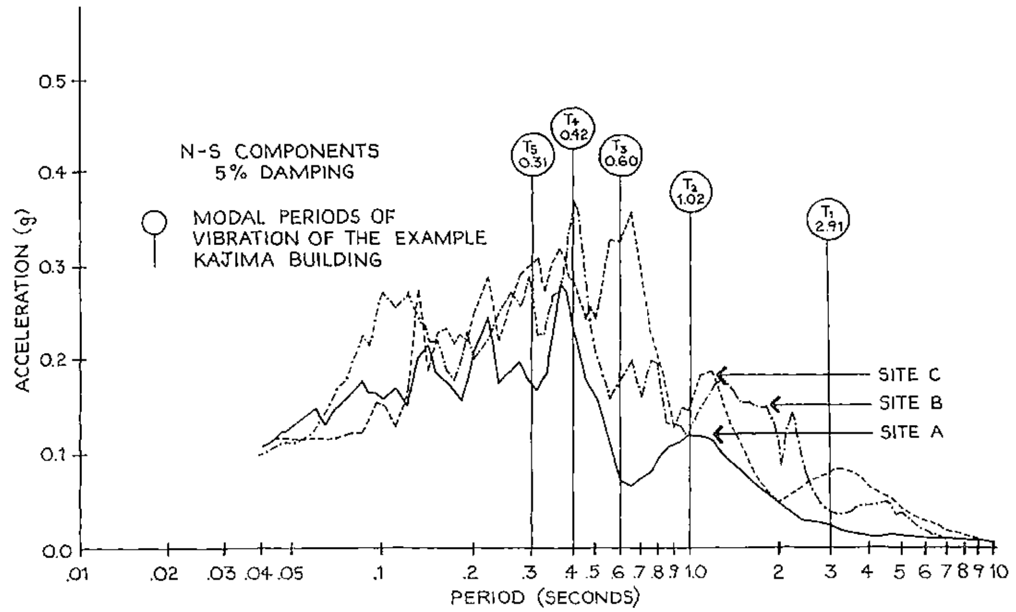


FIGURE A-2. COMPARISON OF RESPONSE SPECTRA FOR SITES A,B, AND C-1971 SAN FERNANDO EARTHQUAKE.

Figure A-2 reveals some general characteristics in the records that are relevant to the effect of a site's geological structure on building response. Records for Sites B and C show greater amplification of response for the range of long periods of vibration than does the record for Site A. These amplifications are due, in part, to local site conditions, but could also be influenced by other factors, such as epicentral distance and the direction of the site relative to the earthquake source. The maximum relative building displacements at each of the three sites are given in Figure A-3 and demonstrate that site conditions can significantly influence the response of buildings. The above results, however, should not be construed as being technically precise: They provide only a general illustration of the fact that site conditions can significantly alter the response of a building. More historical data and research is required before technically precise observations can be made.

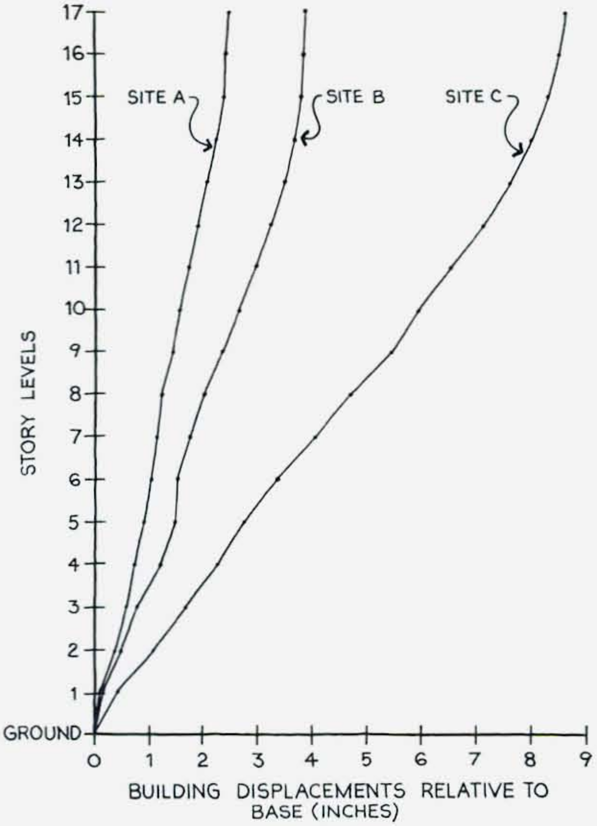


FIGURE A-3. MAXIMUM BUILDING DISPLACEMENTS OF CERTIFIED LIFE AND KAJIMA INTERNATIONAL BUILDING.

EXAMPLE #2: THE EFFECTS OF A BUILDING'S STIFFNESS ON ITS RESPONSE TO INPUT GROUND MOTIONS

To illustrate how stiffness characteristics of a building system can affect its response to input ground motions, an example comparing the maximum responses of two existing buildings as estimated from historical records is presented. The buildings are of similar height, but have dynamic characteristics that are quite dissimilar.

The two structures under consideration are the Certified Life Building and the Kajima International Building. Both are located in Los Angeles, California and both were instrumented with accelerographs at the time of the 1971 San Fernando earthquake. Although the buildings are of similar height, they have quite different lateral force resisting systems, and, as a result, responded quite differently to earthquake input motions. A comparison of relevant information for each building is presented in Figure A-4. The Certified Life Building has a shear wall lateral force resisting system, while the Kajima Building has a moment resisting steel frame system. The first mode period along the north-south axis of each building indicates how much more flexible the Kajima Building is: its fundamental period of vibration of 2.91 seconds is nearly three times longer than the 1.0 second period of the Certified Life building.

Building Data	Certified Life Building	Kajima International Building
Response Type	"Stiff"	"Flexible"
Story Height	14	15
Lateral Bracing	Shear Walls	Moment Resisting Frames
N-S Axis	Transverse	Longitudinal
Modal Periods*:		
First	1.01 sec	2.91 sec
Second	0.21 sec	1.02 sec
Third	0.09 sec	0.60 sec

Ground Motion and Building Response Data	Certified Life Building	Kajima International Building
Distance from Epicenter	17 mi.	26 mi.
Length of Record	36 sec.	24 sec.
Spectral Accelerations at Mode*:		
First	.15g	.08g
Second	.63g	.14g
Third	.44g	.18g
Recorded Maximum Floor Accelerations:		
Bottom	.26g	.11g
Middle	.39g	.21g
Top	.40g	.18g

* Approximate values

FIGURE A-4. COMPARISON OF CERTIFIED LIFE AND KAJIMA INTERNATIONAL BUILDINGS

The spectral accelerations (from recorded data) corresponding to the first three modes of each building (Figure A-4) reveal that the Certified Life Building was subjected to considerably higher accelerations in each node, and this fact is reflected in the maximum floor accelerations that were recorded. Specifically, at the three instrumented floor levels, the maximums for the Certified Life Building were about two times greater than those for the Kajima Building. The computed maximum displacements of both buildings are shown in Figure A-5. The displacements of the "stiff" Certified Life Building are substantially smaller than the displacements of the "flexible" Kajima Building, even though the accelerations of the Certified Life Building are more than twice those of the Kajima Building.

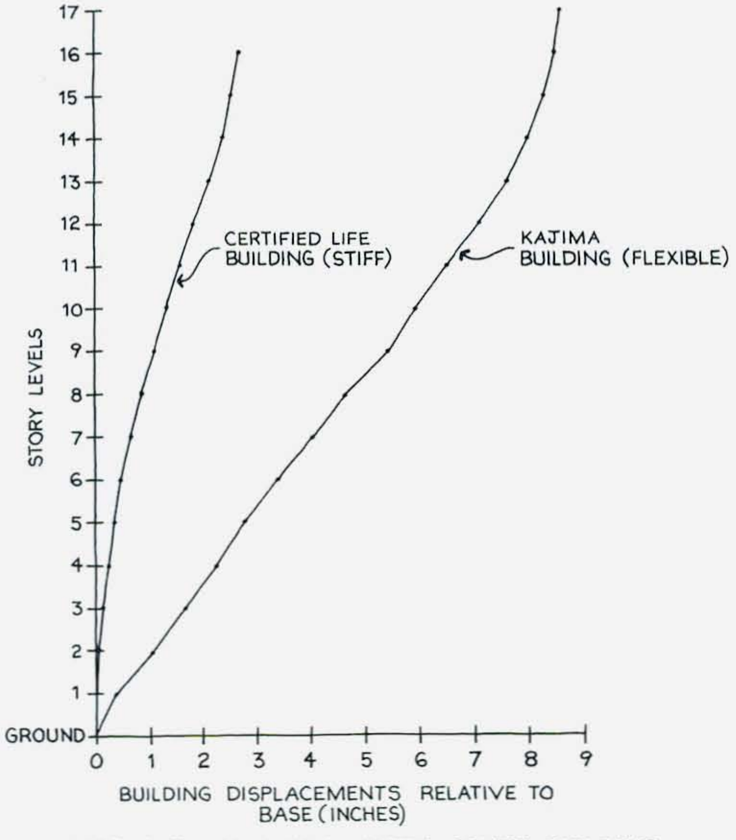
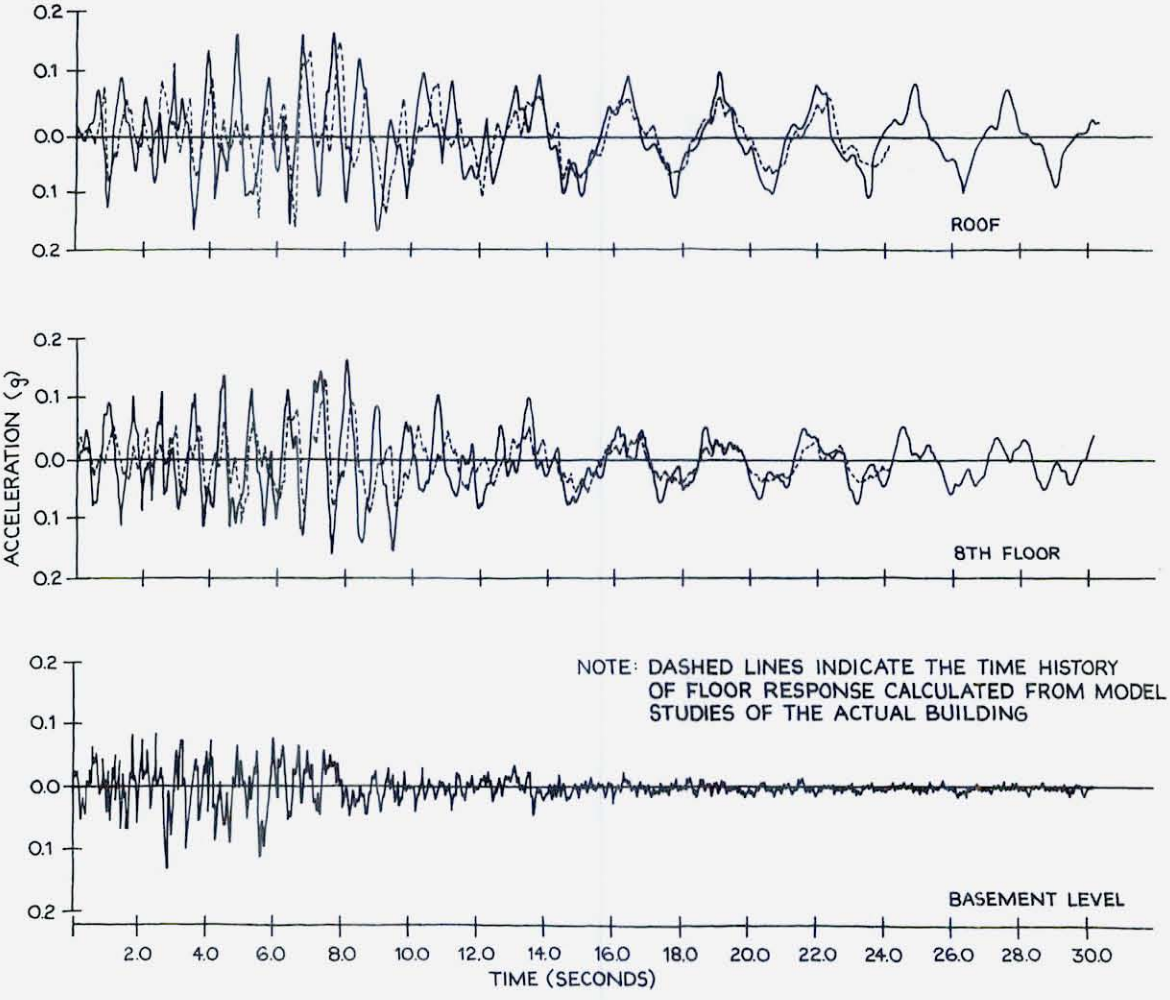


FIGURE A-5. MAXIMUM NORTH-SOUTH BUILDING DISPLACEMENTS OF CERTIFIED LIFE AND KAJIMA INTERNATIONAL BUILDING.

EXAMPLE #3: CHARACTERISTICS OF BUILDING RESPONSE: ACTUAL RECORDS OF BUILDING MOTIONS VERSUS ANALYTICAL STUDIES

Present knowledge of building response to earthquake ground motions has been obtained primarily from records of build-



NOTE: DASHED LINES INDICATE THE TIME HISTORY OF FLOOR RESPONSE CALCULATED FROM MODEL STUDIES OF THE ACTUAL BUILDING

FIGURE A-6. HORIZONTAL ACCELERATION RESPONSE (N 54° W) OF KAJIMA INTERNATIONAL BUILDING.

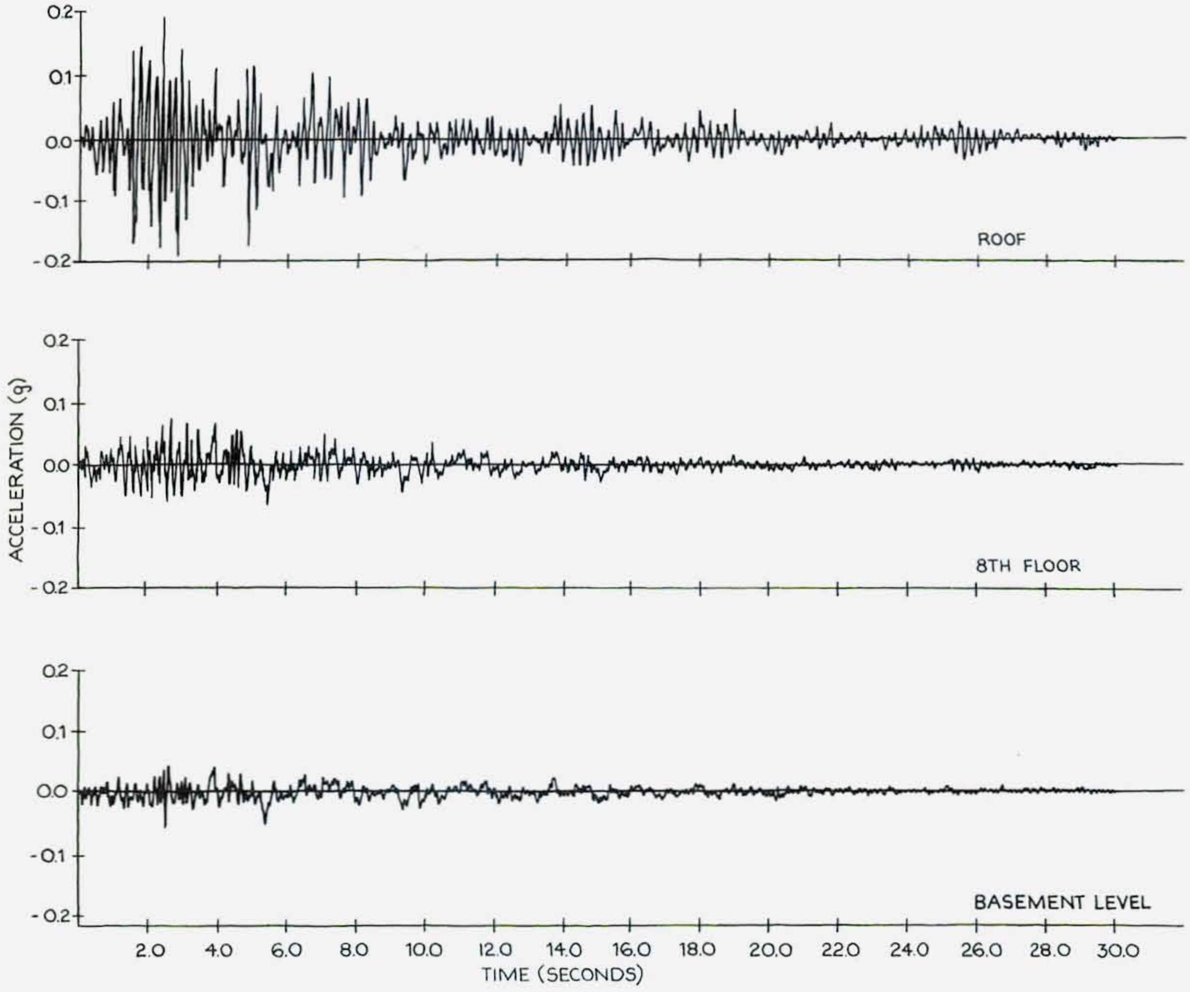


FIGURE A-7. VERTICAL ACCELERATION RESPONSE OF KAJIMA INTERNATIONAL BUILDING.

ing motions during earthquakes, analytical studies of structural response, and observations of building damage. These sources of information help engineers study the structural behavior of buildings during earthquakes, and they aid in the improvement of design techniques. The following example utilizes the first two sources to make some observations on the general characteristics of building response.

Both the horizontal acceleration record in Figure A-6 and the vertical acceleration record in Figure A-7[1] show a noticeable increase in the overall amplitude of response with increase in story height. In addition, the responses at the higher levels are of a more regular cyclic nature than the motions at the basement level. The building acts as a filter and influences the frequency content of the response, amplifying motions at certain frequencies and attenuating motions at others. These observations are fairly typical of the records obtained from other instrumented buildings in earthquakes.

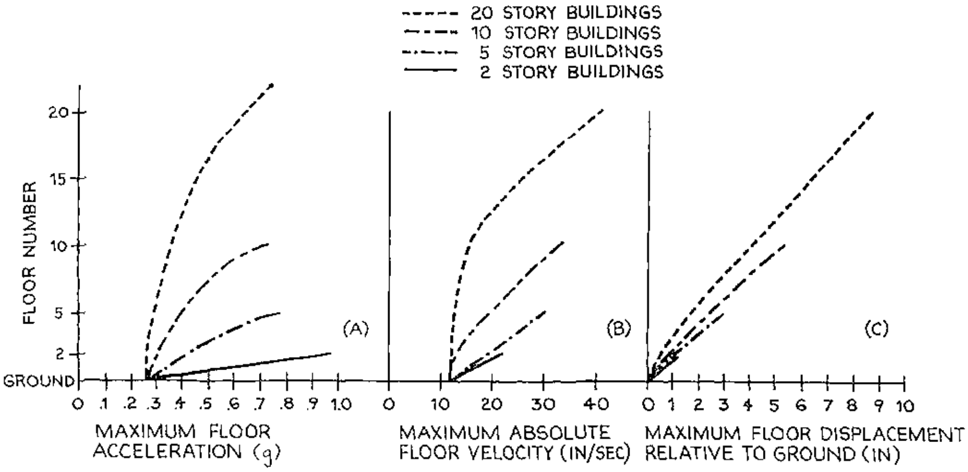


FIGURE A-8. MAXIMUM ACCELERATION, VELOCITY, AND DISPLACEMENT RESPONSES OF BUILDINGS WITH 5% EFFECTIVE DAMPING.

Analytical techniques have been used widely to compute building response to recorded or artifically generated earthquake motions. All analytical techniques require the formulation of a mathematical model of the building system that can be subjected to a ground acceleration time history or a ground response spectrum. This procedure can be used to obtain building responses in terms of maximum values or time histories for accelerations, velocities, and displacements. An example of the typical results of analytical studies is Figure A-8, which shows trends of the variation of maximum building responses with story height. These results were computed from analyses of linear elastic building models of varying dimensions, founded on both stiff and flexible soil types, and subjected to artificial time histories of ground motion.[2]

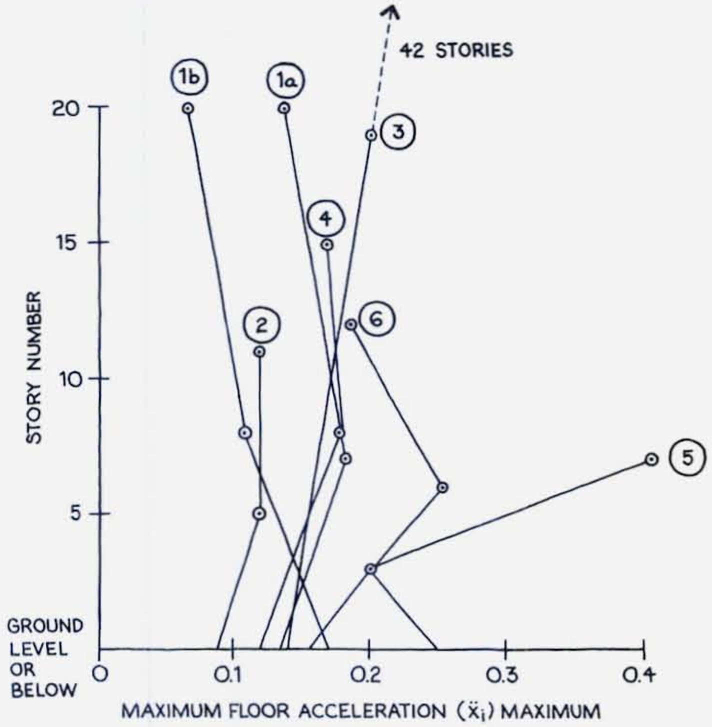
The following summarizes some of the results and conclusions obtained from this study:

- The peak (or maximum) floor acceleration increases with story number such that the highest peak acceleration occurs generally at the highest level.
- The rate of change of peak acceleration decreases with increasing numbers of stories. Thus, tall buildings do not necessarily respond with higher accelerations than do short buildings, given the same loading conditions.
- Low buildings, as well as tall buildings, can develop a high acceleration response if the natural frequency of the building falls within the "resonant" range of the earthquake frequency.

The general implications of the above results for building components are:

- The floor acceleration response is not necessarily highly correlated with the height of the building, but is controlled by the frequency and damping characteristics of the building.
- Rigid components in short buildings might be subjected to accelerations as severe as those in tall buildings.

Analytical results, however, do not always agree with what has been observed in actual structures. Figure A-9, for example, shows the variation in maximum floor acceleration with story height for several buildings in the 1971 San Fernando earthquake. No clearly discernable trends are apparent. Two of the buildings (Numbers 5 and 6) were observed to respond in the nonlinear range. For these buildings the difference in maximum accelerations between floors appears to be greater than for buildings with observed linear responses. Such comparisons of actual records with general analytical results indicate that general trends must not be applied to specific design problems without adequate evaluation of factors that may affect response.



KEY TO BUILDING NUMBERS

NUMBER	BUILDING	AXIS	STORY HEIGHT
(1a)	1901 AVENUE OF THE STARS	TRANS.	20
(1b)	1901 AVENUE OF THE STARS	LONG.	20
(2)	MUIR MEDICAL CENTER	LONG.	11
(3)	UNION BANK SQUARE*	TRANS.	42
(4)	KAJIMA INTERNATIONAL BUILDING	TRANS.	15
(5)	HOLIDAY INN (ORION AVE.)	TRANS.	7
(6)	BANK OF CALIFORNIA	TRANS.	12

* TOP FLOOR RECORD WAS NOT OBTAINED DUE TO INSTRUMENT MALFUNCTION

FIGURE A-9. RECORDED MAXIMUM FLOOR ACCELERATION VERSUS STORY HEIGHT FOR SEVERAL BUILDINGS IN THE 1971 SAN FERNANDO EARTHQUAKE.

EXAMPLE #4: HISTORICAL FLOOR RESPONSE SPECTRA AND THEIR QUALITATIVE EFFECTS ON COMPONENT RESPONSE

To further illustrate the characteristics of floor response to which individual components may be subjected, several historical floor response spectra resulting from the 1971 San Fernando earthquake have been computed for numerous instrumented buildings. Figure A-10 is an illustration of the typical nature of floor response spectra. This example is from the acceleration response of the 1901 Avenue of the Stars Building along the transverse axis at the top, middle, and bottom floor levels. Several observations regarding the nature of floor response and the resulting influence on component response can be made:

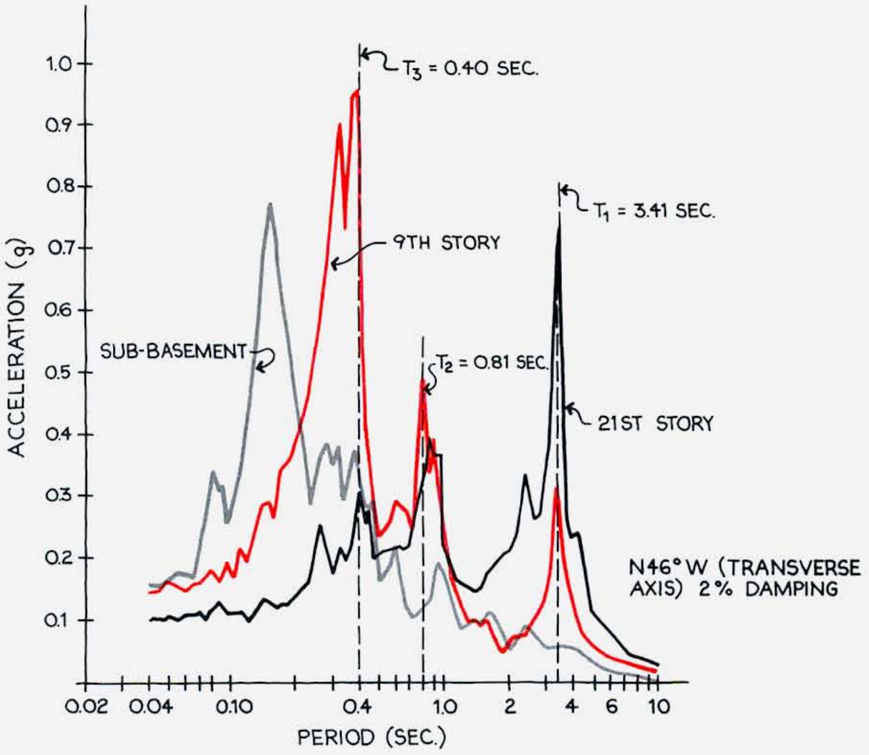


FIGURE A-10. SELECTED FLOOR RESPONSE SPECTRA - 1902 AVENUE OF THE STARS BUILDING.

- The spectra are characterized by major peaks and valleys over a broad range of vibrational periods; two of the predominant peaks are readily identified as corresponding to the first and second mode periods of building vibration.
- Amplification of component response may be high. For example, a component supported at the 21st story level with a fundamental period of vibration corresponding to the first building mode could theoretically attain an acceleration about seven times greater than the maximum floor acceleration. (The assumption is that the component behaves linear elastically under such accelerations.)

Footnotes for Appendix A

[1] M. Leonard Murphy, Scientific Coordinator, San Fernando, California Earthquake of February 9, 1971, U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, 1973.

[2] L. W. Fagel, S. C. Liu, and M.R. Dougherty, "Synthesis of Strong Motion Earthquake Environment in Multistory Telephone Buildings - Case 20133-5," Bell Laboratories Memorandum for File, November 20, 1973.

Appendix B: Time History and Response Spectrum Methods of Calculating the Response of a Structure

There are a number of available methods, with varying degrees of complexity, for dynamic seismic analysis of multi-degree-of-freedom building structures. The methods involve either elastic or inelastic procedures, the former of which are in most frequent use at the present time. A linear elastic dynamic analysis may involve procedures in the time domain, such as the response spectrum or time history methods, or those in the frequency domain, which are finding increasing use, particularly in modeling soil-structure and water-structure interaction effects. In addition, various types of probabilistic analyses may be used. Because most engineers today use linear elastic dynamic analyses involving procedures in the time domain, these methods are presented here.

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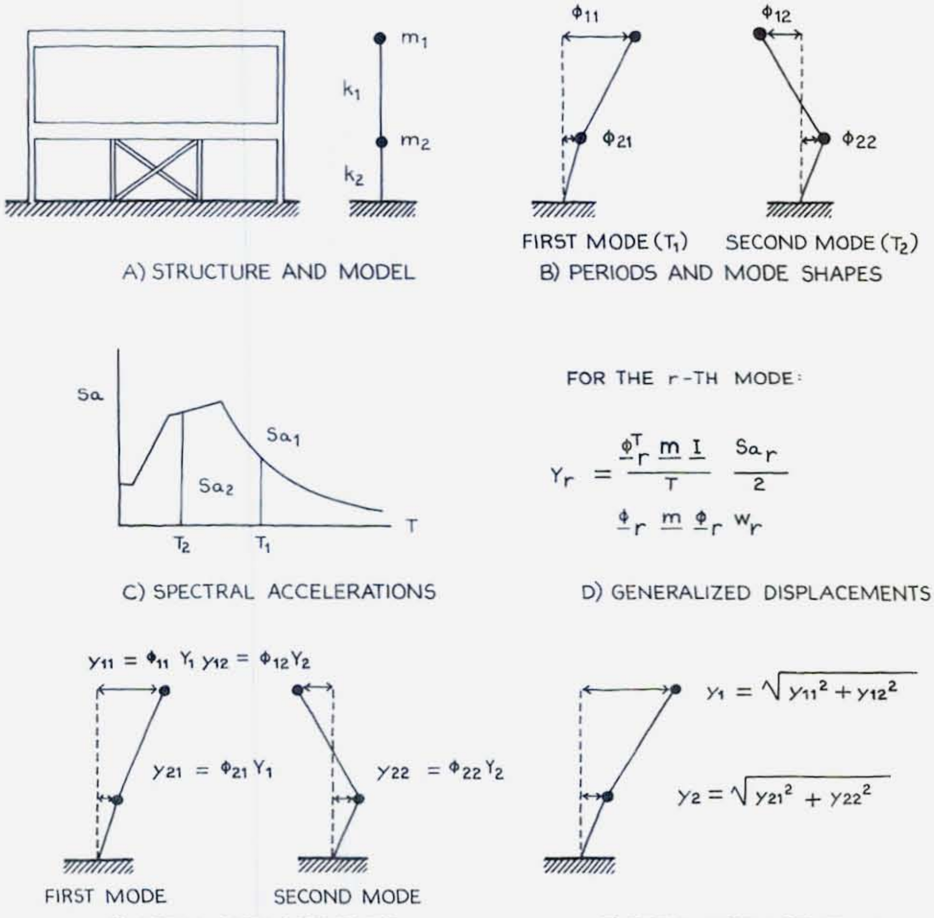
The basic steps in a linear elastic dynamic analysis are as follows. The first step is to develop a preliminary design to size basic members. This preliminary design may be based upon static procedures, requirements for vertical loads, and so forth, depending on the particular situation. An analytical model of the structure is then developed, and appropriate mass, stiffness, and damping characteristics selected. The dynamic characteristics of the structure (natural periods of vibration and mode shapes) are then determined and the response calculated by either the time history or the response spectrum method. The output from such analyses are the displacements, accelerations, and member forces and moments. The analyses should be iterative, perhaps for several earthquakes, or for several sets of model parameters, such as material properties. After the parametric analyses are performed, the appropriate seismic loads are combined with other loads, utilizing appropriate load factors, and the total values are checked against allowable stress or deformation criteria. There may be iterative cycles requiring modification of the design.

The response spectrum method can be described in qualitative terms as follows. The structure and corresponding analytical model are shown in Figure A-11a. The vibrational motions of the linear elastic structure can be assumed to be the sum of the vibrations in two mode shapes, as illustrated in Figure A-11b. After these mode shapes and the corresponding periods have been calculated, the next step is to select spectral accelerations corresponding to these periods for the appropriate damping ratio, as shown in Figure A-11c. These spectral accelerations are then multiplied by the factor in Figure A-11d which is known as the participation factor, and divided by the square of the circular frequency of vibration to produce what is called the generalized displacement. One such quantity is calculated for each mode.

The actual maximum displacements in each mode are calculated as shown in Figure A-11e. For example, for the first mode, the maximum displacement for the first nodal point (roof) is obtained by multiplying the mode shape at that point times the generalized displacement for that mode as shown on the left hand side of Figure A-11e. Thus, at this point, one has calculated maximum displacement of the structure in each of the two modes. The next step is the combination of these maximum modal responses to obtain the total maximum response. The most commonly accepted method is to use the square root of the sum of the squares (SRSS) method to obtain the total response values, as illustrated in Figure A-11f. In this case, the total displacements are obtained as demonstrated. A similar procedure is used to obtain the maximum total moments, shears, etc. (Note that it is not proper to take the maximum displacements obtained as shown in Figure A-11f and from these displacements back-calculate the internal forces and moments.)



A) STRUCTURE AND MODEL

B) PERIODS AND MODE SHAPES

C) SPECTRAL ACCELERATIONS

D) GENERALIZED DISPLACEMENTS

E) NODAL DISPLACEMENTS

F) TOTAL DISPLACEMENTS

FIGURE A-11. DYNAMIC ANALYSIS BY RESPONSE SPECTRUM METHOD.

Dynamic analysis by the time history method is illustrated in Figure A-12. The structure and model are the same as they were for the response spectrum method, as are the periods and mode shapes. Up to this point the analyses are identical, but the calculation of the response from here on varies. The time history of response in each mode is calculated and then these time histories combined to obtain total response. The design value is then selected as the maximum of the total response. This procedure is illustrated in Figure A-12 as follows. In Figure A-12c, the time histories of response due to the input motion time history $y_g(t)$ are calculated. For example, the displacement of the upper node (roof) in the first mode is shown as $y_{11}(t)$. A similar procedure is followed for the second mode. Similar procedures are followed at the same time for the calculation of the internal shears and moments in the various structural members.

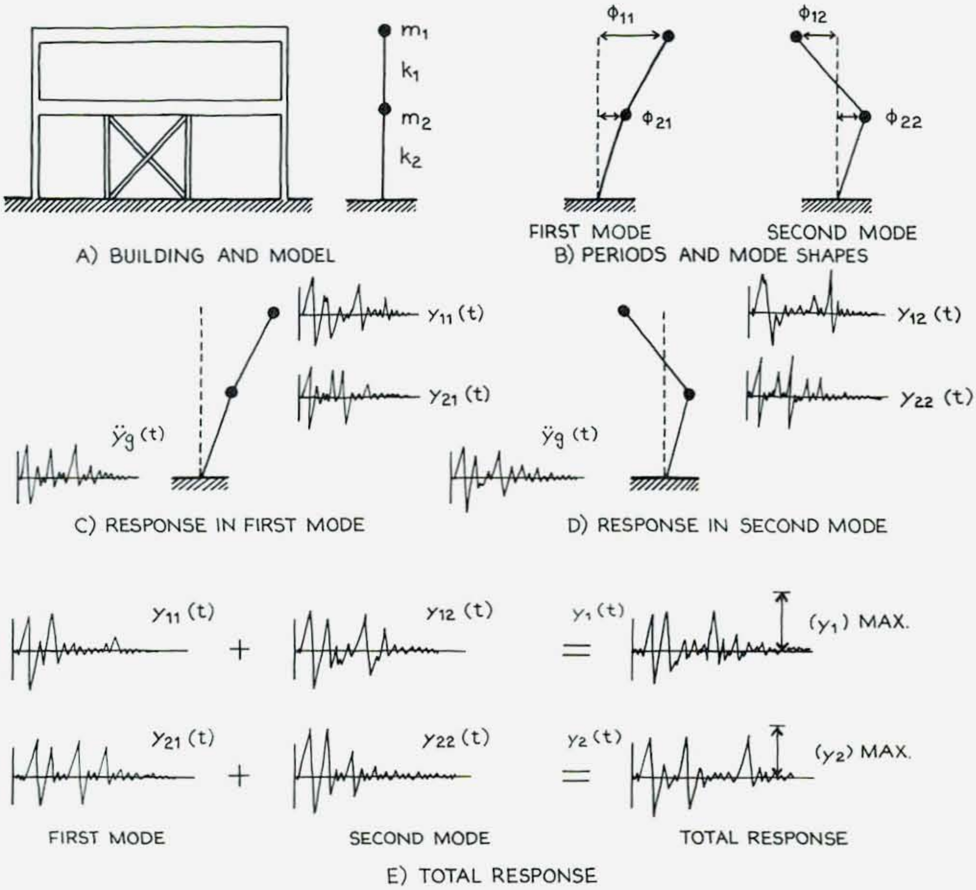
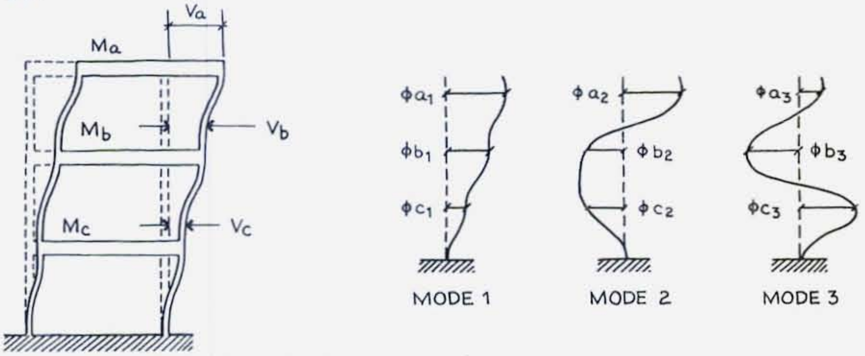


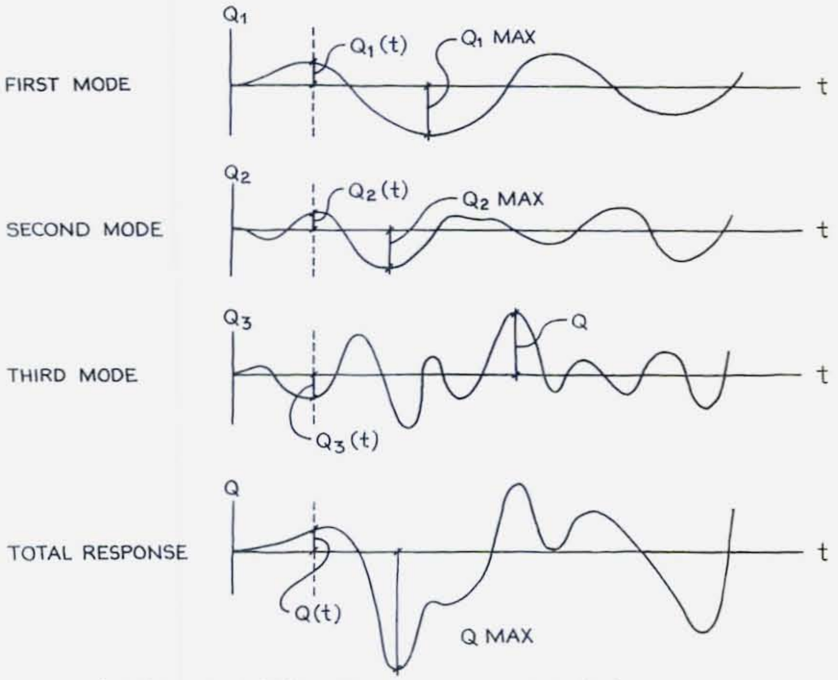
FIGURE A-12. DYNAMIC ANALYSIS BY TIME-HISTORY METHOD.

The next step is to combine the time histories of these modal response quantities as illustrated in Figure A-12a. For example, the time history of displacement response of the top node in the first and second modes are summed on a time-step by time-step basis to produce the time history of the total response of the upper node, $y_1(t)$. The value $(y_1)_{max}$, as shown in Figure A-12e is then selected for use in design. This procedure is further illustrated in Figure A-13.



A) EXAMPLE OF MULTIDEGREE-OF-FREEDOM SYSTEM

B) VIBRATION MODE SHAPES



C) BASE SHEAR RESPONSE OF EXAMPLE BUILDING

FIGURE A-13. MULTI-DEGREE-OF-FREEDOM MODEL.

Comparisons of the two methods have appeared in numerous references, and usually show that the response spectrum method, using the square root of the sum of the squares method for modal combination, is somewhat more economical to use, while the time-history analyses eliminate the bothersome problem of modal combinations, and often result in lower calculated response.

- Because the frequency content of floor motions varies from floor to floor, the largest spectral acceleration at any period of vibration does not necessarily occur at the highest building level. For example, at the sub-basement level the floor spectrum exhibits a major peak around 0.15 seconds, which is significantly larger than the spectral accelerations at the upper levels for this period.

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