THE INTERACTION OF BUILDING COMPONENTS DURING SEISMIC ACTION

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SYNOPSIS

A unified design approach is developed to account for the interaction of building components under seismic loading. A four-part model is presented which provides a dynamic viewpoint for design strategies. This model consists of the ground, the integrated structure, interdependent elements and dependent elements. Enclosure, finish, and service systems may be part of the integrated structure or interdependent or dependent elements, and specific, but significantly different design strategies apply depending upon which of these dynamic roles they perform. Other key issues discussed include the nature of in-building motions and principal design and analysis methods for building components.

INTRODUCTION

The design of buildings to resist earthquakes has quite naturally been concerned primarily with the structure. For convenience of design and analysis, the primary structure of the building has been considered as separate from the finish and service systems. These in turn have been considered as non-structural, even though they all constitute a series of substructures which are part of the building. However, the patterns of damage to such components during earthquakes offer strong evidence to support the conclusion that current design procedures do not adequately provide for the patterns of movement and deformation which these substructures must sustain. Currently, most codes use design criteria for the substructures which are extrapolated from principles developed for the primary structure, but this is often not adequate.

It was therefore apparent that a rethinking of the role which various components of the building system play under dynamic loading was needed. As a result of grants from the National Science Foundation, support was provided for two research projects (Ref. 1, 2, and 3) concerned with developing damage mitigation strategies and improved design procedures for components of the enclosure, finish, and service systems of conventional buildings. The research efforts attempted to put forth a conceptual dynamic model by which the participating design professional can visualize the dynamic interaction of enclosure, finish, and service systems; understand the basic aspects of dynamic response and the physical characteristics influencing the response; and, with this background, systematically follow the

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various damage mitigation strategies to develop the details of the design. (Actual design details were not devised). The efforts were also directed towards establishing a common basis for (1) understanding the phenomena of building response, and (2) developing common problem-solving approaches among the several disciplines who collaborate in the design of buildings.

The projects represented a first-step effort; subsequent work is in progress to apply the conceptual model to an example building design. The following discussions summarize the principal topics in the above investigations.

FOUR-PART DYNAMIC MODEL

The development of a new conceptual model for designing building components was founded upon an extension of the "operational" model into a dynamic context. This latter model envisions a building as an assembly of components which performs various operational functions. These components may be conveniently grouped into two broad categories: those which comprise the "primary structure," or "PS," and those which make up the different enclosure, finish, and service systems, or "EFS." The PS components are elements whose primary operational function is to carry gravity loads (e.g., columns, beams, floors, etc.); although these components may also have the capacity for resisting lateral dynamic loading, initially they are usually conceived for static load requirements. The EFS components include elements such as exterior fascia, interior walls and ceilings, and various mechanical and electrical service systems, as may be found in conventional buildings.

This operational model, for design, was deficient in several important respects; chief among these was that dynamic forces have been approximated as static loads, and each component has been considered in a static frame of reference in which other components of the building are also assumed as fixed. As an improvement over this static frame of reference, a model consisting of four elements was devised for grouping the components of the operational model into a dynamic context which also considers the interaction process among components. This four-part Dynamic Model consists of the Ground, the Integrated Structure, the Interdependent Elements, and Dependent Elements, as follows:

Ground (G): the ground and its characteristics of movement in response to seismic forces must in many cases be considered as an integral part of the building.

Integrated Structure (IS): the combined form of the PS described earlier, and certain components of the EFS, which due to their permanence and physical compatibility including mass, stiffness, strength, etc., may be incorporated with the PS to improve the total response under dynamic loading. The Integrated Structure is designed to provide the dynamic integrity of the building as a whole. The EFS included in the Integrated Structure are components such as shear walls, etc. Because the Integrated Structure provides the dynamic integrity of the building, those EFS components incorporated into it must be identified early in the design process and must be designed for a permanent and fully interactive role as parts of the Integrated Structure. Such EFS components are dynamically coupled with the Primary System.

Interdependent Elements (IE): those EFS components which are not a part of the Integrated Structure, and yet due to their mass, stiffness, strength, connectivity, or other dynamic characteristics, they significantly affect the earthquake response of the Integrated Structure. For this reason, they must be considered in its analysis and design. The Interdependent Elements may make positive or negative contributions to the dynamic integrity of the building and may not be permanent. Examples of such components are heavy or rigid partitions and enclosure walls, major pieces of mechanical equipment, etc. The term "interdependent" arises from the fact that the Integrated Structure influences the response of the Interdependent Element, and conversely, the Interdependent Element influences the response of the Integrated Structure; thus, they are interdependent. Such elements must therefore be considered as dynamically coupled with the Integrated Structure.

Dependent Elements (DE): these components of the EFS, like the Interdependent Elements, are also dependent upon the Integrated Structure and must sustain the movement patterns it imposes. However, these components do not significantly affect the pattern of response of the Integrated Structure, and except for their weight, can be neglected in the seismic design or analysis of the Integrated Structure. Such elements can be considered as dynamically uncoupled from the Integrated Structure.

The above model includes distinctions which are relevant to the design process, even though certain of the analytical procedures are the same. For example, from a technical standpoint, those components of the EFS which are part of the Integrated Structure and those which are Interdependent Elements are all fully interactive with the components of the PS. For both of these groups, the analytical procedures for the structural engineer are essentially the same. But the distinction is an important one for the architect who must normally identify those elements whose function and permanence makes them suitable to be part of the Integrated Structure.

DAMAGE MITIGATION STRATEGIES

The four-part dynamic model provides a means for exploring various design strategies to mitigate damage. These are described in broad terms in order to identify the scope of possibilities available to all professions involved in building design.

The primary causes of earthquake damage to building components involve two types of action: change of shape of the components due to deformation of the structure, and vibration of the components due to their dynamic response. In order to reduce these effects, there are three broad design strategies which can be pursued: (1) reduction of ground input motion, (2) control of building response, and (3) control of building component response.

The first of these basically involves controlling earthquake characteristics, selection of a less hazardous site, site treatment, building isolation, etc. In general, strategies to mitigate damage by altering the ground motion are based upon the concept of reducing the input energy before it reaches the building. At present, most of the proposed schemes do not appear practical; however they may offer future possibilities.

The second strategy is based upon a control of building response through the adjustment of various physical aspects of the Integrated

Structure. In brief, those aspects which provide design control opportunities are the configuration, mass, strength, energy dissipation, connectivity, and stiffness of the building. Depending upon the design objectives and operational requirements of the building, logical alternatives can be readily identified. This strategy offers wide latitude for controlling both inertial and relative displacement effects which directly affect the requirements for building component performance.

The third strategy involves designing building components such that vibrational effects are reduced and expected relative displacements of the supporting primary system are accommodated by the component. Within this approach, the alternatives available to enclosure and finish systems are somewhat different than for service systems due to options in dynamic roles typically available. That is, enclosure and finish systems may play either a dynamically coupled or uncoupled dynamic role with the primary system depending upon the choice of the designer. In comparison, the physical characteristics of many service system components tend to permit them to be categorized solely as uncoupled Dependent Elements (except in the case of heavy equipment).

In the case of enclosure and finish system components, various physical aspects — similar to those available for controlling building response — can be altered in order for the component to play either a coupled or uncoupled role in the building system. Additionally, a "mixed" or "phased damage" approach is also possible which utilizes a combination of the coupling and uncoupling techniques such that for low levels of ground motion, the component remains undamaged and coupled with the primary system; and for higher levels the component becomes damaged in controlled areas and tends toward an uncoupled condition. For any of these approaches, the ultimate goal is to minimize or control damage through recognition of the demands expected on the component as determined by its dynamic role in the building system.

In the case of mechanical and electrical service systems, the design strategies are oriented around an accommodation of the inertial and relative displacement effects imposed upon such components by the earthquake response of the building. If the nature of in-building motions are known (in terms of floor response spectra) along with the expected relative displacements of the primary system, then certain design strategies can be developed to minimize possible damage to the components. These strategies involve either designing for the postulated forces and displacements or reducing the effect of component response through (1) increasing the frequency of vibration, and/or (2) utilizing energy dissipation techniques. Such approaches are systematically explored through a consideration of various physical properties (e.g., mass, stiffness, etc.) of the component and its support as discussed in References 2 and 3.

THE NATURE OF IN-BUILDING MOTIONS

A key issue in the development of the above strategies involves knowledge of the amplitude and frequency content of floor motions. A summary of some of the general findings obtained from the review of a sample of historical records of floor motion and analytical studies are given below:

- The variation in maximum floor acceleration with height was not seen to agree with results typically observed from analytical studies. However, a review of the general character of time histories of floor acceleration did appear to verify this trend. This gave rise to the question of whether the maximum floor acceleration is the appropriate parameter with which to gauge this phenomenon.

- The influence of the structure in governing the nature of floor motions was clearly apparent in both the time histories of floor response and the response spectra of the buildings reviewed. The peaks in the spectra were seen to be associated with various modes of building vibration; this was shown with certainty at the first mode. Also, at the first mode period a general increase in amplification of component response above maximum floor acceleration is noted with increase in height in a building. This was not generally the case at other building periods.

- The floor response spectra reviewed exhibited significant peaks of amplification throughout a broad frequency range. Thus it was apparent that the various analysis and design approaches which consider only the effect of the amplification of component response around the first mode of building vibration may be markedly unconservative.

From the above findings there were direct implications to various design strategies for building components. Additionally, it was felt that a possibility exists to further develop approximate procedures for constructing floor response spectra through additional detailed reviews of historical spectra as well as various parametric analyses of a variety of building types and geological sites; such an approach could avoid the need to resort to detailed dynamic analyses for conventional building design.

REVIEW OF DESIGN AND ANALYSIS METHODS FOR BUILDING COMPONENTS

A review was conducted of the principal methods available which allow for either the prediction of floor motions or the direct specification of design forces. Typically analytical procedures provide a means for constructing floor response spectra while static force approaches specify directly design forces. General comments on each of the principal approaches are: (1) the time history method remains at present the most rigorous and universally accepted procedure available; however, it is the most computationally detailed of all methods; (2) the stochastic and frequency domain methods are recent developments which seem to compare favorably with the time history method while utilizing a design ground response spectrum; these methods deserve further study; (3) response spectrum methods are generally semi-empirical in nature; at present they may be considered as approximate or preliminary procedures which warrant further refinement; (4) the static force approach, as typically adopted by most building codes, is the simplest and most approximate of all available methods; there is little to no rational consideration given in this method to the dynamic properties of the building system so that considerable improvement is necessary.

SUMMARY

The four-part conceptual model appears to offer a highly useful means for establishing design objectives and exploring design strategies to reduce earthquake damage to building components. Other areas of investigation involving the nature of in-building motions and analytical design procedures offer the possibility of future development of approximate approaches which can rationally account for dynamic effects without detailed analyses.

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