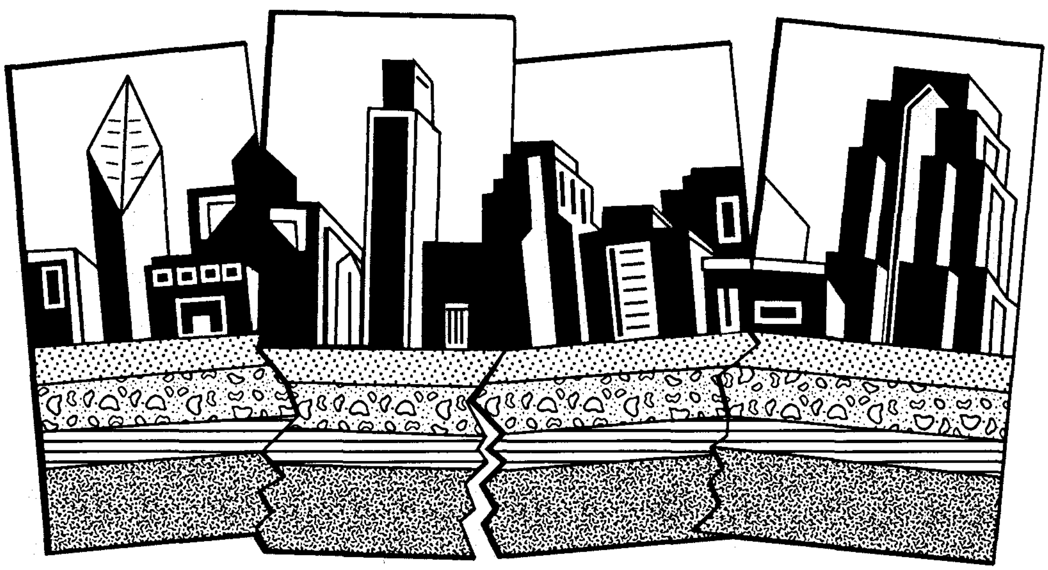
PERFORMANCE BASED SEISMIC DESIGN OF BUILDINGS



AN ACTION PLAN FOR FUTURE STUDIES

ISSUE PAPERS

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EARTHQUAKE ENGINEERING RESEARCH CENTER

PERFORMANCE BASED SEISMIC DESIGN OF BUILDINGS

AN ACTION PLAN FOR FUTURE STUDIES

PREPARED FOR
FEDERAL EMERGENCY MANAGEMENT AGENCY
1 JULY 1996

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DISCLAIMER

FORWARD

One of the primary goals of the Federal Emergency Management Agency (FEMA) is the reduction, or mitigation, of this country's losses due to natural hazards. In order to achieve this goal, we as a nation will need to examine the question of what level of performance do we expect from our buildings during an event such as an earthquake.

It is for this reason that FEMA is very interested in the development of "performance-based design" criteria. Such criteria could be voluntarily used by this nation's engineers and designers to significantly improve the performance of critical classes of buildings that are currently only designed to a "lifesafety" level to avoid collapse, but would probably still suffer significant structural and nonstructural damage in a design event.

FEMA contracted with the Earthquake Engineering Research Center (EERC) (contract number EMW-93-K-4253) to solicit the input of the nation's leading seismic professionals in developing an action plan that could be used to develop performance-based design criteria. This project broke new ground in identifying key issues and research needs that will need to be addressed in this process. However, this agency has several concerns regarding the action plan itself.

To avoid further delay, FEMA has decided to publish this document as a "final draft" for informational purposes only. Publication of this document in no way obligates this or any other Federal agency to any portion of plan contained herein. The information and opinions contained in this document are solely those of the contractor and do not necessarily represent the views of FEMA.

In closing, FEMA sincerely wishes to express its gratitude to all who were involved in this project. Drs. Jack Moehle and Andrew Whittaker of EERC, the members of the Issues Identification Team, Project Review Panel, Issue Paper Writers and the Colloquium attendees all contributed significantly to this effort. The results of their hard work will play an important role as this country moves forward towards performance-based design.

EXECUTIVE SUMMARY

Introduction

This report sets forth an action plan for the development of new design procedures and guidelines directed towards the establishment of *performance based seismic design*. These procedures are directed towards overcoming key deficiencies in our current design practice.

Current seismic design codes and practices were written to achieve a loosely defined objective of providing building occupant safety. While this objective has been reasonably well achieved, two major shortcomings are recognized. The first shortcoming lies in the realization, made clear by recent earthquakes, that buildings designed to provide occupant safety may incur extensive structural and non-structural damage, often resulting in huge economic losses for building owners and the community, and loss of function for weeks or months. While casualties have been relatively small (in comparison with other earthquake-prone areas of the world), tens of billions of dollars in direct losses are associated with recent U.S. earthquakes. The second shortcoming is that our seismic design measures are very unevenly applied; some buildings are subject to costly over-design, while other critical or economically important buildings suffer large losses because designs are not properly related to performance needs and expectations.

Expert design professionals and researchers believe that sufficient knowledge now exists, or can be relatively easily obtained, to enable seismic design to be much more closely geared to real building seismic behavior, thereby meeting in realistic terms the expectations of building owners. This view of the future of seismic design is termed *performance based seismic design*. The thrust of this approach is to make building performance in earthquakes predictable, and better related to the owners' and society's needs and resources.

This project will provide seismic design procedures that are documented in guidelines and commentary that can form the basis of a new generation of seismic codes, and enable designers and owners to expect a new level of predictability in performance for future buildings. In so doing, a new balance between design objectives and design methods can be achieved that will result in overall economies over the lifetime of our building stock while providing building owners and the public with much greater assurance when the earthquake strikes. This in turn will enable lenders and insurers to predict earthquake losses with much more accuracy, and government response and recovery agencies to plan for known earthquake consequences.

This project responds to a need expressed by the Building Seismic Safety Council and others in a number of reports to the Federal Emergency Management Agency (FEMA). To meet that need, FEMA organized a preliminary study in which experts from various disciplines and varied geographic regions of the United States examined the issues, possibilities, problems, and opportunities, of performance based seismic design. The preliminary study resulted in an action plan. This report contains that action plan.

The action plan recognizes earthquakes as a natural environmental problem that may occur anywhere in the nation, and therefore pose a national threat that will always be present. The passage of time only increases the danger. The plan also recognizes the need to address the problems of existing hazardous construction along with new construction. Design procedures and guidelines developed by the execution of this action plan will be readily exportable to other seismic design guidelines so that all civil engineering and lifeline structures can be designed or upgraded to meet specific performance objectives. The action plan is coordinated with other related efforts at the national and state levels, and by the private sector, and is designed to reinforce those related efforts.

Program Expectations

The effort described by this action plan covers a span of six years. At the end of that period, the execution of this action plan will result in the following specific products:

- Acceptable definitions of different performance levels.
- The technical basis necessary for achieving target seismic performance levels in new and existing buildings, including benefit/cost analysis procedures.
- Guidelines and commentary for implementation of performance based seismic design of new buildings, and rehabilitation of existing buildings.
- Educational materials and programs targeted at university educators and students, design professionals, and building owners and users.
- A framework to allow for the future inclusion of new analysis and software technologies in the Guidelines.
- A national information electronic database to aid planners, policy makers, design professionals, researchers, and others to obtain needed information relating to performance based design.

Products will be delivered at interim stages over the course of the six years. In a process similar to that employed by the Applied Technology Council on the project funded by FEMA to develop seismic rehabilitation guidelines (ATC 1995), interim guidelines will be published for review at the 25%, 50%, and 75% completion milestones. These submittals will be published for review by the project team, expert design professionals and academicians, and key building officials.

Program Benefits And Costs

The program should result in considerable savings in terms of life cycle building costs, achieve reductions in direct and indirect earthquake losses, and produce a more sustainable society. The federal government, state governments, private industry, and the general public will each realize the net benefits. Improved seismic reliability will enhance the national security. The effort will also result in improved international competitiveness for United States firms.

There is a short-term cost necessary to achieve the net long-term benefits that will accompany the implementation of *performance based seismic design.* While this cost is substantial, it should be recognized that this sum is a minute fraction (less than 0.01%) of the total annual construction expenditure (approximately $450 billion) in the United States. It is also a small fraction of the losses commonly associated with a moderate or severe earthquake in an urban area, as was made clear by the 1994 Northridge and 1995 Hyogo-Ken Nanbu earthquakes.

The many beneficiaries of this program, including the federal government, state government, and private industry, must share the associated costs. The action plan proposes lead organization(s) for each task and sub-task in part to emphasize the need for lead direction and funding from a variety of Federal, State, and private agencies and organizations. It was the consensus of the experts involved in the project that the first-year start-up costs, and some of the continuing program costs, should be borne by the federal government.

Planning Assumptions

The key assumptions of the action plan include the following:

- **High level coordination and oversight of the action plan tasks.** The execution of the action plan in a cost-effective and timely manner will require subtask integration and coordination, fiscal and administrative support, liaison with related projects and groups, and interaction with funding agencies. Task 1.1 of the action plan creates a strong management plan for this purpose.
- **Commitment to the six-year effort by the dedication of resources at the level recommended in the action plan.** The action plan describes an effort extending over a period of six years. The schedule of work as proposed is extremely

aggressive. Sufficient resources should be appropriated at the beginning of the project to execute the action plan in its entirety.

- **Interim product delivery.** The project deliverables, namely the guidelines and the commentary, will be published for detailed review and comment, at the 25%, 50%, 75%, and 100% completion milestones. Review of the format and thrust of the deliverables, at these key milestones, will promote the rapid acceptance of the final documents by the end users on completion of the project.
- **The need for early action.** Several tasks in the action plan must begin as soon as practical to obtain early success because these successes lay the foundation for work on other tasks and subtasks. Refer to Chapter 6 for a brief description of these tasks. The start-up tasks will probably require federal funding in order to bring other funding sources, such as the NEHRP agencies, federal and state government departments, and the insurance and construction industries, on line.

TABLE OF CONTENTS

Chapter 1
INTRODUCTION

Performance Based Seismic Design

As evinced by the public response to the behavior of building, lifeline, and infrastructure facilities in recent earthquakes in California, the performance of the built environment during moderate to severe earthquake shaking has not met societal expectations.

Performance based seismic design aims to produce buildings that perform during earthquakes according to expectations and with greater economy. A key beneficiary of performance based seismic design will be the civil infrastructure in the United States.

Performance based seismic design allows building owners to define performance levels to meet the specific requirements for the building and its contents; sample performance levels may include: collapse prevention, life safety, damage control, and maintained operations. Performance based seismic design will also allow lenders, insurers, and government response and recovery agencies to help reduce the impact and cost of future earthquakes. Expert design professionals and researchers view performance based seismic design as the seismic design approach of the future. Moreover, performance based seismic design is a major move toward a more holistic approach to maintaining a sustainable society. This report presents an action plan, the goal of which is the timely development of the technical basis for performance based seismic design criteria for buildings.

Current U.S. building design codes do not adequately address the issue of building seismic performance (BSSC 1991). Building codes primarily address life safety, and are intended to control damage in minor and moderate earthquakes, and to prevent collapse in major earthquakes. However, the actual reliabilities of the current codes are not known. Options for alternate performance goals such as continued function are not addressed in detail by current codes. Furthermore, there is no direct consideration of economic loss resulting from an earthquake.

Recent earthquakes in the western United States have demonstrated that events of moderate earthquake magnitude can have staggering economic consequences. These events have surprised government officials, building owners, and the public in general, who expected that buildings designed to current building codes would be "earthquake proof." While the economic consequences of these recent earthquakes have been great, they pale by comparison with expectations for a great earthquake. We need improved design procedures that result in better performance, and we need to better communicate the performance expectations and the associated costs to the public. Performance based seismic design approaches can be developed that achieve these goals.

Earthquakes are a national problem, not just a regional problem. The economic impact of a major earthquake will be felt throughout the United States. Further, evidence points out that earthquakes can happen almost anywhere in the United States. Experts are now concerned that design ground motion levels are not in balance from one region of the United States to another, and that levels in moderate and low hazard areas may be too low to offer worthwhile protection (BSSC 1991). Performance based seismic design procedures need to be developed that offer uniform protection to all regions of the United States.

A large percentage of the building stock throughout the United States was constructed either without consideration of seismic resistance or before the requirements of earthquake resistant construction were fully understood. As a result, many buildings in all regions of the country pose a hazard should they be subjected to moderate or strong ground shaking. Procedures are needed for the redesign and upgrading of these potentially hazardous buildings. The basic procedures developed for performance based seismic design would apply equally well to the upgrading of existing construction as to the design of new construction.

The development of seismic design codes in the United States traditionally has relied on the part-time efforts of volunteer experts. This process has been successful in maintaining and incrementally updating our design codes. Though seismic design codes in the United States are now among the most advanced in the world, it is recognized that the current process of their development is not conducive to major innovation or to advancement of significant new knowledge. A move in the direction of performance based seismic design is a move toward a completely new generation of seismic design codes. It cannot be achieved through the usual process in a timely and effective manner. A focused effort is needed. This action plan is an attempt to define that effort.

The effort represented in this action plan is not intended to pre-empt or duplicate other related activities. Instead, this effort will build on the findings of those activities and provide resource material to enhance those activities. The related activities include: The Building Seismic Safety Council *NEHRP Recommended Provisions* (BSSC 1991), the Structural Engineers Association of California (SEAOC) Vision 2000 effort, the ATC/NCEER study of critical code issues, ATC-34 (ATC 1996), and the FEMA Guidelines and Commentary for the Seismic Rehabilitation of Buildings project, ATC-33 (ATC 1995). Leading experts working on each of these projects have contributed to preparation of this action plan, and many are expected to contribute to its execution.

Scope Of The Action Plan

The action plan provides for the development of the technical basis for performance based seismic design, and the publication of related guidelines and commentary for the implementation of performance based seismic design.

The tasks described in this action plan include development of the technical basis necessary for performance based seismic design for new buildings, and for evaluation and upgrading of existing buildings. For this purpose, the action plan outlines the studies needed to: define performance goals; define economic incentives and legal issues; inventory and synthesize performance data; develop design guidelines and commentary; conduct benefit/cost case studies on target buildings; support research; and develop associated educational and information dissemination materials.

The requisite studies described in this action plan include improved definition of important parameters associated with strong ground motion and other earthquake hazards but excludes earthquake hazard mapping. As part of the BSSC NEHRP Provisions update, an on-going parallel national effort is being funded by USGS to improve earthquake hazard maps. This project, identified as Project 97, includes both national and regional mapping efforts, and is due for completion in the year 2000. Project 97 should continue in parallel with the efforts described in this action plan so that a cohesive pair of products, one on performance based seismic design procedures and another on seismic hazard definition, can be linked before the completion of this effort.

The action plan does not include mandated implementation of performance based design procedures into codes of practice. This should be carried out by the existing code writing organizations following completion of this effort. However, the plan anticipates this process by including in all of its tasks careful consideration of the adoption of performance based seismic design into codes and standards.

Preparation Of The Action Plan

The Federal Emergency Management Agency (FEMA) is the lead agency responsible for coordinating the federal government's National Earthquake Hazards Reduction Program (NEHRP). Reducing the impact and cost of future earthquakes through mitigation actions is a major component of NEHRP activities, and FEMA has recently elevated mitigation to the Directorate level. As such, FEMA has a vested interest in encouraging the development of performance based seismic design criteria.

The Building Seismic Safety Council (BSSC), as part of its 1991 revision of the *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings*, reported to FEMA that "... research is needed to provide rational and explicit performance levels ..." In response to that expressed need, FEMA contracted with the Earthquake Engineering Research Center at the University of California at Berkeley to develop an action plan for the development of performance based seismic design criteria. The plan development process required input from organizations and specialists in earthquake engineering from around the United States.

In consultation with the FEMA Project Officer, the Earthquake Engineering Research Center formed an Issues Identification Team (IIT) to review available information and relevant activities, and to define key issues associated with development and implementation of performance based seismic design. The IIT presented the results of their study to a Project Review Panel (PRP), whose task it was to provide independent review and project oversight. Seven key issues emerged:

1. Definition of Performance Goals and Criteria
2. Format, Enforcement, and Implementation
3. Risk Assessment and Structural Reliability
4. Structural Analysis and Design
5. Performance of Soils and Foundations
6. Performance of Structural Components and Systems
7. Performance of Nonstructural Components and Systems

Nine expert design professionals and researchers were retained to author Straw Man Issues Papers on these seven issues. These papers were presented and discussed at a two-day User Needs Colloquium held in San Francisco on 27 and 28 January 1994 (less than two weeks after the M6.8 Northridge earthquake in southern California). The User Needs Colloquium brought together more than 50 earthquake engineering experts from different regions of the United States. The two day Colloquium included plenary sessions and seven concurrent breakout sessions during which general consensus was reached on the main issues and future study needs. The Colloquium discussions provided a basis for redrafting the Straw Man Issues Papers, and the preparation of draft action plans for resolution of outstanding items in each of the seven key issues. Appendix A lists the IIT and PRP members, Straw Man Issues Paper writers, and Colloquium attendees.

Following the Colloquium, the IIT coalesced the separate draft action plans into a single draft action plan that was distributed for review to the PRP, Straw Man Issues Paper writers, and Colloquium attendees. Discussions at two subsequent meetings with the PRP, and two reviews by the Colloquium attendees, produced the present version of the action plan.

Whereas the program was initially organized along the lines of seven key issues represented by the Straw Man Issues Papers, the final program is re-drawn in terms of two elements that embody the ideas of the seven key issues. These are:

- Element 1: Planning, Policy, Management, and Implementation
- Element 2: Technical and Design Requirements

Element 1 contains tasks related to overall project management of the action plan, investigation of appropriate performance goals, identification of key milestones, economic and legal issues, and implementation. Element 2 includes tasks related to inventory and synthesis of performance data, identification of appropriate design approaches, technical support of performance based seismic design procedures, preparation of guidelines and commentary, and benefit/cost studies. For each task there is a proposed start and finish time and estimated dollar cost. Summary schedules and summary costs are also provided.

The action plan describes a concerted effort extending over a six-year period. The schedule of work as proposed is extremely aggressive. In order to execute the action plan in its entirety in six years, resources should be appropriated at the beginning of the project to ensure funding at the requisite level is available for the duration of the project.

The execution of the action plan in a cost-effective and timely manner will require strong management, subtask integration and coordination, fiscal and administrative support, liaison with related projects and groups, and interaction with funding agencies. Task 1.1 of the action plan creates a management plan for this purpose.

The action plan anticipates interactions and contributions from a broad constituency. This includes agencies of the federal, state, and local governments; professional trade groups; private industry; professional practitioners from the design, construction, and legal professions; and university educators and researchers.

Program Expectations

By the end of the six years covered by this action plan, the following should be accomplished, given effective implementation, and funding at the recommended levels:

- Acceptable definitions of different performance levels will have been developed.
- The technical basis necessary for the development of performance based seismic design procedures will be prepared and documented, including analysis and design methodologies, risk assessment procedures, and benefit/cost decision-making procedures.

- Guidelines and commentary for implementation of performance based seismic design of new buildings, and rehabilitation of existing buildings, will be complete.
- A framework for including new analysis procedures and related software tools in the guidelines will have been developed and implemented.
- Educational materials targeted at university educators and students, design professionals, building officials, building owners, and users will have been prepared and disseminated. Nationally applicable university course materials on performance based design will have been developed and implemented at a minimum of two leading universities.
- A national information electronic database will be established to aid planners, policy makers, design professionals, researchers, and others to obtain needed information relating to all aspects of performance based design — this informational service will be a national resource.

Report Organization

The report is organized in seven chapters. Chapter 1 defines performance based seismic design and describes the various elements of the action plan. The action plan is divided into two elements.

The action plan for Element 1 is presented in Chapter 2. This chapter details aspects of the action plan dealing with planning, policy, management, and implementation. It includes the program management structure, investigation of appropriate performance goals, identification of key milestones, economic and legal issues, and development of educational materials. The action plan proposes lead organization(s) for each task and sub-task in part to emphasize the need for lead direction and funding from a variety of federal, state, and private agencies and organizations.

The action plan for Element 2 is presented in Chapter 3. Chapter 3 details aspects of the action plan dealing with technical and design requirements, and research needs including inventory and synthesis of performance data, identification of appropriate design parameters, development of performance based design guidelines, benefit/cost case studies on selected buildings, support for a research program on performance based seismic design, and support for improved post-earthquake studies. Similarly to the action plan for Element 1, the action plan for Element 2 proposes lead organization(s) for each task and sub-task.

The recommended sequence for the tasks comprising the action plan and key milestones in the process is described in Chapter 4. The tasks recommended for early action are detailed in Chapter 5. References are presented in Chapter 6. A summary of the benefits and costs of the proposed action plan is presented in Appendix A. A list of project management and technical participants is presented in Appendix B.

Chapter 2

ACTION PLAN FOR ELEMENT 1: PLANNING, POLICY, MANAGEMENT, AND IMPLEMENTATION

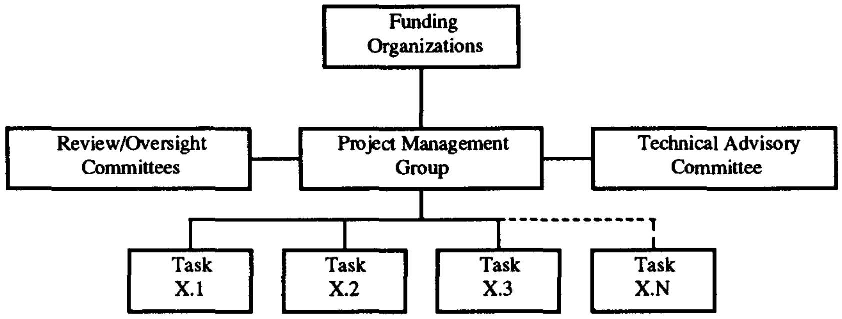
Task 1.1 - Establish Program Management

This action plan to develop procedures for performance based seismic design of buildings will involve numerous subtasks, and will require close coordination of the various tasks and subtasks. Such coordination is critical in order to make the most effective use of the considerable funding that will be required for this project. Furthermore, there is a need to foster the implementation of performance based seismic design as the various procedures are developed. Task 1.1 is to establish a strong management group and the supporting infrastructure that can efficiently carry the program to its successful conclusion.

Specific responsibilities of the management group include:

- Overall project management.
- Technical project management.
- Fiscal and administrative support, including dissemination of funds by subcontracting various tasks.
- Liaison with other projects, the user community, professional and technical groups, and other external entities, including joint activities utilizing memoranda of understanding.
- Interaction with funding organizations, and development of status reports on milestones and schedules.
- Advisory group and other meeting support.

An organization chart illustrating relationships to the management group, as well as its responsibilities, is shown below.



The management group will require at least one full-time individual with technical expertise in the area of performance based seismic design of buildings who will be the Project Management Group Director, five quarter-time technical experts, two full-time administrative assistants, an office facility, and supporting expenses (including a considerable travel budget). Specifics concerning constituency and location of the management group should be established considering recommendations from technical experts as well as from the funding organizations. The project management group will require fiscal support for the duration of the project and must be empowered to make management decisions within the scope of the project. The annual cost for this task is not constant over the six-year period; the breakdown is presented in Table 1.2.

Duration: 6 years

Lead Organization: NEHRP Agencies

Task 1.2 - Investigate User Needs

Performance based design, incorporating different performance levels and objectives, will be implemented as a guideline but could be adapted into a code. A building code should provide a community approved minimum threshold of criteria for public health, safety, and economic well-being of the community. A guideline for performance based design, besides considering the minimum threshold, would contain procedures intended to achieve performance levels exceeding the community approved minimum threshold. Some basic questions therefore arise. What are the minimum and alternate performance levels? Who would be the users of standards for alternate performance levels? How would building owners utilize these guidelines? For what types of buildings would performance based procedures be most used? What percentage of seismic design would seek alternate performance levels? What are the reasons for choosing alternate performance levels, and what incentives or policies would encourage their use? What are the performance expectations of owners, investors, insurance companies, designers, etc.?

Subtask 1.2.1 - Identify Users and Their Needs

Possible users of alternate performance levels include lenders, insurance companies, government agencies, and building owners. Each of these users may choose alternate performance levels for a different purpose and may implement them in a different way. Each will view costs and benefits differently. Some will consider only short-term economic gain, others will take a longer economic view, and some will be guided by societal and other factors.

Different users may define the minimum acceptable performance level and the alternate performance levels differently. Therefore, the definition of the minimum and alternate performance levels should be re-evaluated with input from the building users, building officials, and building design experts. Current design codes provide a starting point for defining a minimum threshold for performance. However, consequences of recent earthquakes raise the question of whether the currently implied performance objective is acceptable to the community of building users. User-friendly language and terminology to define the various performance and risk levels will be developed.

Performance based design guidelines should be oriented toward what the various members of the building community would use. Target building types emphasized in the standards should be consistent with those types for which the guidelines would most likely be used. Finally, the level of effort to be directed toward developing the guidelines should be influenced, among other things, by the overall expected level of use.

This task should identify users of alternate performance levels, identify performance goals and language, identify target building types, and estimate the percentage of buildings that would be designed to standards exceeding the minimum mandated by codes of practice. The study would establish on a regional basis the percentages of current building designs that are based on minimum code levels versus alternate performance levels. The study should also convene a workshop involving experts from the building design and end-user communities to identify likely future users, likely performance levels and appropriate language, and uses of performance based guidelines. This task will take advantage of developments in the FEMA Guidelines project on the seismic rehabilitation of existing buildings (ATC 1995), and will enhance that activity.

Duration: 1 year

Lead Organizations: FEMA, NIST

Subtask 1.2.2 - Investigate Economic and Policy Issues

In order to decide whether to design for enhanced performance objectives, the owner of a building must address fiscal issues associated with increases in construction costs and long-term (or life-cycle) savings. Implicit in this statement is the expectation that improved performance will usually cost more — although performance based seismic design should be able to identify some inefficiencies in current design practice and thus reduce cost. Ultimately, the number of owners who would choose a higher level of performance than the code-mandated minimum will be very much affected by the additional first cost, and the degree to which reduction in life-cycle costs can be made convincing. Fiscal incentives for building owners may need to be developed by economists and social scientists. Incentives may also be needed for vendors of building contents to make their components more earthquake resistant without significant cost increase to building owners and contractors.

Economics is not the only basis for making a decision regarding performance level. Business goals and other factors enter into the decision-making process regarding desired performance (currently, many decisions to upgrade performance are made without any formal benefit/cost analysis). There will always be some percentage of owners who, for business reasons, have no interest in long-term cost. Because some owners have goals that are inconsistent with the overall long-term economic well-being of the community, regulation may be needed to ensure that all owners consider long-term cost as part of the public interest, similar to the rationale for energy codes.

This task should evaluate the economics of alternate performance levels. The study should identify reasons for choice/rejection of improved performance levels, including documenting case histories where individuals have selected alternate performance levels based on existing methodologies. Aspects of incentives and regulation should be investigated. A workshop involving design professionals, property investors, construction economists, social scientists, and other end users will be held to identify and evaluate benefit/cost issues, identify incentives for future use, and recommend appropriate policies. Such a workshop will be coordinated, and perhaps held in conjunction with the workshop recommended under Subtask 1.2.1.

This cost benefit data will be refined as the performance levels and related criteria are developed. Further, this work will utilize existing material and data, such as the cost-benefit model that has been developed for FEMA (1992a).

Duration: 1 year

Lead Organizations: FEMA, Insurance Industry

Task 1.3 - Study Use of Performance Specifications and Aspects of Certification

A significant proportion of the total value in a building lies in nonstructural components, including built-in architectural, mechanical, and electrical components, as well as contents and furnishings. Few of these components are designed specifically for earthquake effects. Most are designed primarily considering other aspects, and are either modified during installation for seismic actions or are simply put into service without consideration of earthquake effects. If performance based seismic design is to have a significant impact on the overall building system performance, it must consider these currently elusive elements of the system.

Indeed performance based seismic design has implications far beyond the single problem of seismic performance and should be seen as responsive to future directions of the design and construction industry. While new practices such as construction management, sophisticated cost estimating, and design-build procurement have provided some answers to building owners who are concerned with building cost and construction schedules, the design professions see issues of quality becoming lost in a trend towards bottom-line objectives and short-term economic horizons. Moreover, buildings still continue to be assembled using labor practices and conditions that have changed little in the last fifty years.

Performance based seismic design must be seen as but one of a family of environmental concerns, along with the indoor climate, acoustics and lighting, fire safety and weather protection, and interior and exterior finishes that are all performance related. To achieve predictability in all these aspects will require an introspective review of the way the construction industry works: many believe that future expectations for the building industry that are in tune with other sectors of the economy can be achieved only in the development of basic building system prototypes, which can be combined together to create buildings and complexes. Precedents exist for these approaches that need to be studied in relation to current conditions, and performance based seismic design provides a good entry point into such studies.

If the code does not define performance specifications above the yet-to-be established minimum threshold, there is a need for some entity that does, and this or another entity should certify that a given design will provide the desired level of performance. Performance based design may require a higher level of quality control to guarantee that a building is constructed as designed. Furthermore, once a structure design and original construction are certified, there may be a need to track possible changes in performance over time resulting from deterioration or from building modifications.

Development and adoption of contents specifications and certifications will likely lead to improvements in overall performance. They are also likely to lead to additional costs that would tend to lessen the owner's enthusiasm for the performance approach. Costs are associated with initial specification and certification, special inspection during construction, and tracking and re-certification over the life of a building. The issue comes down to: What level of construction can we afford, or are the levels that we currently accept lower than are prudent?

Subtask 1.3.1 - Develop Inventory of Specifications for Building Components

A study that will produce an inventory of currently available specifications, guidelines, and standards, will be conducted. The study will identify significant building components and systems without specifications. The inventory should cover built-in components, contents, and furnishings. The inventory should consider aspects of new construction and aspects of modifications or deterioration following issuance of the building's occupancy permit.

Duration: 1 year

Lead Organizations: NIST, Industry

Subtask 1.3.2 - Study Alternate Procedures for Specification and Certification

A study will be conducted of alternate procedures for pre- and post-installation specification and certification of building components, with identification of necessary institutional entities. The study will include (a) procedures for quality control and reliability, (b) procedures for re-certification against change, and (c) impact of additional procedures on end users. The study will be developed through preliminary study and a workshop involving end users, certification groups, and building designers.

Duration: 1.5 years

Lead Organization: Industry

Task 1.4 - Investigate the Roles of the Design and Construction Professions

The traditional model of the design and construction process envisages a fragmented group of professionals responsible for various technical aspects of the project, coordinated (and generally hired) by the architect, who acts as the voice of the design team to the owner. The design team produces contract documents; there is a contract selection process, and the selected contractor is charged with executing the design for a fixed sum in accordance with the plans and specifications. The contractor in this model is out of the decision-making loop; contractors do not participate in design decisions but simply follows plans and specifications.

Rather than drawing lines around professional areas of understanding and responsibility, the complexity of modern design and construction will best be served by increased interaction within the design and construction team and with its client. Performance based seismic design encourages, or even requires, a move in this direction because it forces discussion of fundamental project objectives at the initiation of a project that have implications for the whole team as it proceeds down its design and construction path.

The new procedure will change the roles of the project principals and will require project team partnering. The owner will have to make decisions and understand performance alternatives that previously were not required of the owner, in part based on technical and economic advice from the project team. The engineer will play a pivotal role in the implementation of performance based design. Furthermore, contractors must be able to implement performance based design drawings and specifications so that the resultant buildings achieve the explicit performance goals. Given these new requirements, the roles and interactions of members of the design team need to be examined and perhaps re-defined.

A study is required to inventory and classify the activities of the various participants in the building project, and to identify common interaction problems that affect achievement of performance objectives. The optimal roles of the participants should be investigated. Legal and liability implications associated with implementing performance based design should be investigated. These aspects should be explored by development of position papers and discussion in a workshop which primarily addresses architectural and engineering practitioners, building officials, construction oriented legal professionals, construction managers and contractors, and insurance representatives. An industry-wide reference document on design responsibility should be developed.

Duration: 2 years

Lead Organizations: Design Professional Organizations, Construction Industry, Insurance Industry

Task 1.5 - Develop Educational Materials

The implications of a performance based approach are very large, particularly when issues of reliability, certification, and re-certification are considered. The process is much more complex than dealing with minor code changes every three years. The various users would need to develop an understanding of the material specifically generated to address their concerns and levels of technical understanding.

Subtask 1.5.1 - Performance Levels and Objectives

Most members of the building community do not have a clear sense of what level of performance is expected using current, single-performance level codes. In a performance design environment, building designers will need to understand more clearly the various levels and objectives of performance, and will need to be able to convey these to building users and constructors. A set of educational materials will need to be developed that describes the performance levels and resulting risks in technically meaningful and user-friendly language. The audience would include building designers, equipment and contents vendors, lenders, insurance companies, the community, and building owners. This task should not begin until Subtask 1.2.2 is completed and must be coordinated with Subtask 1.5.

Duration: 1 year

Lead Organizations: FEMA, NSF

Subtask 1.5.2 - Performance Based Design Procedures

Along with needing to understand the various performance levels and objectives, building design team members will need to understand performance based seismic design procedures. The procedures are likely to be more complex than current procedures, offering alternate analysis/design paths to achieve alternate performance levels. A series of educational materials should be developed describing techniques for performance based seismic design. The materials will demonstrate practical applications of the guidelines developed under Task 2.4. The audience would include engineers and architects. Note that Subtask 1.5.2 focuses on design procedures whereas Subtask 1.5.1 addresses more conceptual issues, and is aimed at the broad constituency involved in design and construction of the built environment.

Duration: 1 year

Lead Organizations: FEMA, NSF, Design Professional Organizations

Subtask 1.5.3 - Regional Training Courses

Develop and hold regional training courses on performance based design, addressed to the different user sectors. The costs include development of course materials and the first series of courses. Course materials will include that developed in Subtasks 1.5.1 and 1.5.2. Additional courses to extend beyond the initial six years of this action plan are outside the scope and budget of this subtask.

Duration: 2 years

Lead Organizations: FEMA, Design Professional Organizations

Subtask 1.5.4 - Implement A/E Education Packages

Performance based seismic design requires a new way of thinking about seismic design. It also requires extensive cooperation of individuals working in different disciplines. Current academic programs in most educational institutions do not emphasize this interaction and integration. Support is needed for institutions to develop and implement interdisciplinary educational programs in this subject area. The materials developed in Subtasks 1.5.2 and 1.5.3 would be used as appropriate for the different A/E audiences.

One focus would be architectural education programs because of the key role architects play in the design process. First, architectural decisions, particularly those related building configuration and nonstructural components, could negatively influence the validity of any performance statements because architectural design goals are often in conflict with the goals of the structural engineer. Second, architects are typically the source of technical information to the client (though this role is tending to reduce as alternate methods of project procurement proliferate). The architect would need to be well informed in performance based design to explain the implications to the owners and ensure that all decisions were made in a timely manner. At present, many projects are developed in which issues of seismic performance are not a subject of discussion because the owner assumes that code level design is taking care of his/her seismic problems and, instead, architect/owner discussion focuses on matters of "real" concern such as schedule, planning, costs, materials, finishes, etc.

Another focus would be engineering education programs because engineers are often responsible for delivering a structural skeleton that in large part controls the overall performance. Changes in engineering programs are needed that would improve the engineer's understanding of architecture, risk and reliability, economics, building function, and overall system performance.

This task should convene leading educators to discuss needed changes in academic programs necessary for implementation of a performance design standard. Trial programs should be implemented and supported at two or more of the leading universities located in different geographic regions of the country.

Duration: 4 years

Lead Organizations: FEMA, NSF, State Agencies

Task 1.6 - Information Dissemination Program

Successful implementation of a performance based seismic design procedure will require the designer to have access to more, and more-readily available, information. The appropriate model for disseminating this information is not immediately clear. One model is development of a national information service that would serve as a repository and would provide ready access through an electronic network. An alternate model would be development of an "encyclopedia of seismic performance" that could be updated continuously and issued in some format to design professionals. This subtask should have as its goal the investigation of an appropriate information model, as well as its implementation. This task will be most effective if it supports one or more of the existing information programs in earthquake engineering (National Information Service for Earthquake Engineering at the University of California at Berkeley and the California Institute of Technology, and the Information Service at the National Center for Earthquake Engineering at SUNY, Buffalo), rather than initiating an entirely new program.

Duration: 4 years

Lead Organization: FEMA, NSF

Task 1.7 - Project Deliverables: Guidelines and Commentary

Key to the success of the proposed program is the on-going support and input from the constituency potentially impacted by the implementation of performance based design procedures. Such support and input can be realized through the publication and promulgation of the guidelines and commentary as they are developed. A successful example of this strategy is the FEMA-supported project to develop guidelines for the seismic rehabilitation of buildings (ATC 1995) wherein guidelines and commentary are released for review and comment at the 25%, 50% , 75%, and 95% submittal milestones. The requirement for on-going review and comment ensures maximum input from the aforementioned constituency, and thus potentially immediate implementation once the guidelines and commentary are completed and released.

Guidelines and commentary should be released for review and comment at the 25%, 50% and 90% submittals. The 25% submittal should be released at the end of Year 2, and should include the format of the 100% submittal. The 50% and 90% submittals should be released for review at the end of Year 3, and mid-way through Year 4, respectively. The final product comprising the guidelines and the commentary, should be delivered at the end of Year 6.

Duration: 6 years

Lead Organization: FEMA

Schedule Of Work For Element 1

Table 1.1 presents a draft schedule for the tasks of Element 1 of the action plan. The tasks are interwoven with related tasks in Element 2. Logical inter-relations and timing of tasks are described in Chapter 4.

Table 1.1: Draft Schedule for Element 1

Task	Year											
	1		2		3		4		5		6	
1.1 Program Management	■	■	■	■	■	■	■	■	■	■	■	■
1.2 Investigate User Needs												
1.2.1 Identify users and needs	■	■										
1.2.2 Investigate economic/policy issues			■	■								
1.3 Performance Specifications/Certification												
1.3.1 Building components specifications	■	■										
1.3.2 Alternate procedures			■	■	■							
1.4 Roles of Design/Construction Professions			■	■	■	■						
1.5 Develop Educational Materials												
1.5.1 Performance levels and objectives					■	■						
1.5.2 Design procedures							■	■				
1.5.3 Conduct regional training courses									■	■	■	■
1.5.4 A/E educational packages					■	■	■	■	■	■	■	■
1.6 Information Dissemination Program					■	■	■	■	■	■	■	■
1.7 Project Deliverables				■		■		■				■

Chapter 3

ACTION PLAN FOR ELEMENT 2: TECHNICAL AND DESIGN REQUIREMENTS

Task 2.1 - Inventory and Synthesize Available Performance Data

Development of technically sound performance design procedures requires an improved understanding of performance characteristics of building components and contents. Included here are structural and nonstructural materials, structural and nonstructural elements and components, conventional and innovative structural systems, and building contents. A significant amount of analysis, testing, and field data collection has taken place in the past. Much of the collected data has been synthesized for use in our current codes, that is, a code with a single nebulous performance goal. There is a need to re-examine and synthesize available data on behavior so that performance can be quantified over an entire range. Specifically, this task is to identify behavioral characteristics (damage states) that can be related to performance levels in Task 2.2. This synthesis exercise therefore will be directly useful for developing the performance procedure, and will also serve to identify areas where further data collection and research are required.

Several subtasks for synthesis are identified below. These tasks should be closely coordinated and managed to avoid excessive overlaps or gaps.

Subtask 2.1.1 - Synthesis of Performance Data on Building Contents

This task involves reviewing existing databases and recorded observations in past earthquakes to collect and synthesize performance data on building contents. Buildings contain a wide variety of contents, which may vary with time, and which are usually selected and installed without the advice of the building designers. (An exception to this rule occasionally occurs, e.g., in museums where protective systems may be employed directly to protect the collection.) Recognizing that the building designer usually cannot control the performance of contents directly, the designer should strive to control the response of the contents indirectly by controlling the response of the building. The essence of this task is to synthesize data on contents performance, perhaps in the form of user manuals, to aid the designer in selecting performance parameters for future building designs.

Specifically, this task should categorize building contents according to performance categories (or levels), aspects of building response that influence the performance, consequences of various performance levels, and options for mitigation. Types of possible performance categories for different contents vary considerably; some contents may have only two well-defined performance levels (a computer is either undamaged if it stays in its cabinet or totally destroyed if it falls out) whereas others have a range of (perhaps less well defined) performance levels. The potential consequences of various performance levels on life safety, property loss, and loss of function should be identified. The review should also identify where knowledge gaps exist.

This task will provide input to and interact with Task 2.2.

Duration: 1 year

Lead Organizations: NEHRP Agencies

Subtask 2.1.2 - Synthesis of Performance Data on Nonstructural Components

This task involves review of existing databases (e.g., the SQUG data collected for the nuclear industry) to collect and synthesize performance data on nonstructural components. Buildings contain a wide variety of nonstructural components that clad the building, ensure building function, protect the building and its contents, and enable ingress and egress. Most of these elements and systems are designed and installed by the building design team. Therefore, the design team has an opportunity, not always exercised in current designs, to design for seismic performance objectives. The essence of this task is to synthesize information on behavior of nonstructural elements so that it will be useful to the designer in selecting performance parameters for the nonstructural elements and the entire building.

Specifically, this task should collect and synthesize data on behavior/performance of nonstructural elements (cladding, partitions, ceilings, mechanical equipment, sprinkler systems, etc.) at various limit states as a function of imposed loading (deformation, acceleration, force, etc.). The review should include anchorage systems and protective systems (conventional isolation joints, base isolation, etc.). The potential consequences of various behaviors on life safety, property loss, and loss of function should be identified. The review should also identify where knowledge gaps exist.

This task will provide input to and will interact with Task 2.2.

Duration: 2 years

Lead Organizations: NEHRP Agencies, Industry

Subtask 2.1.3 - Synthesis of Performance Data on Structural Materials and Elements

This task reviews existing databases to collect and synthesize performance data on structural materials and elements. Materials used in modem construction consist primarily of structural steel, structural concrete, masonry, wood, and soil. Composites of these basic materials have been used, and other recently developed materials (e.g., for seismic isolation and passive energy dissipation) have also been proposed. Elements are assumed to include individual elements such as beams and columns, and subsystems such as moment resisting space frames. Most of these materials and elements are selected/designed by the building design team. Therefore, the design team has an opportunity to design for seismic performance objectives. Extensive study has been carried out in the past; however, much of the research was carried out with the limited objectives of determining minimum reliable strength and providing maximum "constructable" ductility. To meet performance design objectives, there is a need to re-evaluate existing data to determine real behavior at a variety of limit states.

Specifically, this task should collect and synthesize data on behavior/performance of structural elements and materials at various limit states as a function of imposed loading (strain, curvature, drift, force, etc.). The review should include typical and innovative materials and elements. The review should also identify where knowledge gaps exist. Key to this task is the development of a national archive for experimental data.

This task will provide input to, and should be coordinated with Task 2.2.

Duration: 2 years

Lead Organization: NEHRP Agencies

Subtask 2.1.4 - Synthesis of Performance Data on Structural Systems

This task reviews existing databases and analytical procedures to collect and synthesize behavior/performance data on structural systems. The review should first identify and categorize modem structural systems (including innovative systems) using a procedure similar to that used to categorize existing buildings. For each system, existing data and analytical procedures should be compiled that would allow correlation between element characteristics, system characteristics, and performance level. The review should also identify where knowledge gaps exist.

This task will provide input to and will interact with Task 2.2.

Duration: 2 years

Lead Organizations: NEHRP Agencies

Task 2.2 - Relate Design Parameters to Performance Levels

A building is a combination of several systems including structural systems, nonstructural systems, and contents. The overall performance of a building in an earthquake is a function of the performance of these systems. Before writing design guidelines, it is necessary to identify how the performance of individual systems relates to performance of the entire building. Specifically, it is necessary to identify which systems are important to achieving each performance level, and to define how to measure the relation between system/element/component performance and overall building performance.

This task is interwoven with Task 2.1.

Subtask 2.2.1 - Relate Damage Limit States to Performance Levels

This task serves to coordinate and refine activities carried out under Task 2.1. Whereas the goal of Task 2.1 is to collect existing data on behavior/performance of building contents and systems, the goal of Subtask 2.2.1 is to prepare a summary identifying key contents and systems and to relate their various limit states to user-defined performance levels. To achieve this goal in a timely manner, Subtask 2.2.1 will receive input from the Task 2.1 teams, identifying key components and systems and their behavior limit states. The results will be presented in a workshop. The key objective of the workshop will be to relate the various behavior limit states for contents and systems to the user-defined performance levels. Results will be summarized in performance tables that relate various limit states for different contents and systems with the various performance levels. The results should be in a format that is usable by Subtask 2.2.2.

Duration: 1 year

Lead Organizations: NEHRP Agencies

Subtask 2.2.2 - Relate Design Parameters to Damage Limit States

Seismic response of different components/systems important to particular performance levels will be dependent on different design parameters. The parameters could include induced stress, strain, drift, acceleration, velocity, energy, number of cycles, etc. These parameters will form the basis of performance based seismic design, guiding the designer in selecting building configuration, stiffness, strength, and other characteristics.

Parameter definition will be relatively straightforward in some cases; for example, a closely fit gypsum partition will pose a property loss risk when lateral drift reaches a critical value. Parameter definition in other cases will be less straightforward; for example, corner columns in a moment resisting space frame may pose a significant life safety hazard when the three-dimensional actions (bending moments, shears, axial forces, and torsion) reach a critical point. It is expected that initial designations of parameters can be achieved by using information available from Tasks 2.1 and 2.2.1. This task will also identify where additional research is needed.

Besides clarifying further research needs, this task will tabulate for various systems/components a proposed set of parameters and suggested values for various performance levels.

The reconciliation of design parameters to damage limit states should be undertaken by teams of experts in the response of: structural materials (structural steel, reinforced concrete, reinforced masonry, timber, etc.); nonstructural elements (cladding, partitions etc.); and, building contents. These concurrent efforts should be coordinated internally by the team leaders, and externally with related projects by the management team.

Duration: 1 year

Lead Organizations: NEHRP Agencies

Task 2.3 - Evaluate Analysis/Design Methods

A major drawback of seismic design procedures incorporated in current building codes is that they are indirect in their approach to achieving performance goals. Structures are analyzed for subjectively modified ground motions using simplified dynamic analysis methods that do not account for expected behavior, are evaluated considering estimates of response parameters often unrelated to those anticipated during actual earthquakes, and are detailed using prescriptive procedures seldom based on realistic calculations of seismic demands and capacities. Such codes are based in part on design experience, post-earthquake damage investigations, and, to a lesser degree, theory and research. There is an increasing feeling that modern structures so designed are generally "safe", yet little indication can be gleaned regarding the degree and economy of the provided safety, and even less can be projected about actual performance over the range of expected events. A key challenge for performance based seismic design is to devise a consistent, realistic, yet practicable, reliability-based framework within which the designer can ensure that a new or existing building will likely respond under the ensemble of design earthquakes in conformance with explicitly stated performance goals.

One approach to resolving the performance based design problem is to devise analytical procedures capable of reliably predicting seismic behavior of all building types in all geographic regions. This approach is likely to bear fruit for certain building types (those requiring and receiving significant engineering design attention) and certain geographic regions (where engineers are well versed in advanced earthquake resistant design methodologies). However, clearly this approach is not appropriate for all situations. Simple prescriptive design tools, based on sound technical principles and calibrated for common conditions and certain classes of structures (e.g., small residential buildings), are also needed.

This task evaluates the efficacy of currently available design and analysis tools for achieving performance based seismic design objectives. It also identifies needed changes in design and analysis approaches, and information needed to support those new approaches.

Subtask 2.3.1 - Investigate and Define Ground Motion Parameters

It is well recognized that peak recorded ground acceleration is not a reliable indicator of building response or damage. Other factors, including ground displacement, ground velocity, frequency content, input energy, and duration, have been suggested as potentially improved indices. To date, no consensus has been reached on this issue, with the result that design earthquakes are often defined subjectively using effective peak accelerations and modified spectral shapes. These ad hoc modifications obscure the relation between input, response, and performance. Further complications arise due to special siting conditions; in particular, concern has been raised over the response of buildings located on soft soil or near active faults. Another concern is seismic environments where the earthquake reasonably anticipated during the lifetime of the building differs substantially from the maximum credible event.

Design issues related to these considerations need to be investigated systematically. Once important ground motion parameters are identified, they can be used in regional or national mapping efforts. The use of hazard maps as opposed to design maps needs to be investigated; a design map may lose its usefulness in a performance based seismic design environment in which there exists a range of design performance objectives and in which new technologies are expected to be introduced in rational ways.

Seismic hazard analysis, both probabilistic and deterministic, will most likely form part of a generalized performance based seismic design procedure. Standardized procedures should be developed for seismic hazard analysis. To develop standardized procedures, attenuation laws that vary as a function of earthquake magnitude, source characteristics, proximity to the causative fault, and local and global geology should be developed and ratified for use by research and design professional seismologists, including both geotechnical engineers and structural engineers.

This task should review data from post-earthquake reconnaissance inspections and detailed investigations to provide real-life insight into the relation between ground motion and seismic performance. Data from detailed analytical and experimental studies of the performance of buildings to various types of ground motion should also be evaluated to complement the limited amount of direct earthquake damage data. These studies should identify critical characteristics of ground motion that can be used for regional mapping of the seismic environment used in building design.

It will be desirable to gather and disseminate knowledge to experts from a variety of fields to assess the broader implications of the ground motions found to influence building performance. Experts from seismology, geophysics, geology, geotechnical engineering, structural engineering, and architectural systems should be involved. Of concern is the reliability with which these parameters can be estimated, and a refinement of terms so that ground motion specialists can most effectively help in establishing design earthquakes for performance based seismic design.

Coordination with ongoing related efforts by the United States Geological Survey, Building Seismic Safety Council (Project 97), and the Applied Technology Council (ATC 1994) will be a key priority to avoid duplication of effort, to foster cooperation between the project teams' members, and to maximize the benefit of the investigations performed under this sub-task.

Duration: 2 years

Lead Organizations: NEHRP Agencies

Subtask 2.3.2 - Evaluate Available Analysis/Design Methods from a Performance Perspective

Simply speaking, where analysis is used in building design, the analytical procedure should accurately reflect the building response and performance to a specified ground motion. Where prescriptive procedures are used, the prescriptions should lead to performance results that reasonably approximate the performance objectives, and, where necessary, should do so for a range of input motions and performance objectives.

It is doubtful whether currently used analysis and design methods satisfy the needs for performance based seismic design. Currently, it is common to execute a design and judge the expected global performance of an entire structural system on the basis of base shear strength and maximum interstory drift index in the direction of each principal axis of the structure. Furthermore, design and evaluation are commonly made based on elastic analysis, so that the only important parameters in analysis are the ground motion representation (often a response spectrum), the elastic stiffness, and the strength. Other methods of analysis have been developed and verified to various degrees including inelastic pushover analyses and nonlinear dynamic analysis; some of these are more suitable to design evaluation than are others. Along with considering analysis and design methods that relate to the global response, there is a need to consider analysis and design methods that relate global response to local response, and that relate local response to proportioning and detailing requirements. The study should include review and evaluation of methods for selecting modeling parameter values (stiffness, strength, damping, etc.).

Current methods for analysis and design, while incorporating elements of uncertainty in the ground motion and materials behavior definitions, are largely deterministic. Furthermore, they tend to deal only with response and design of a single structure for a single event. To minimize the impact of earthquakes on society, there is a need to be able to consider the response of an inventory of buildings, as well as to be able to consider the response of a specific building or the inventory to a single or to multiple events. It is uncertain whether adequate tools currently exist to deal with these needs.

This task should evaluate currently available methodologies for analysis and design for use in a performance based seismic design procedure. The available methods should be described. Their applicability to the range of target building types' should be reviewed. The ability and usefulness of analysis methods to reflect actual behavior, and the efficacy of design methods to achieve desired results over the range of performance objectives, should be reviewed. Methods for integrating performance for multiple events and for building inventories should be reviewed. The review should not be limited by perception of regional engineering experience and education, but should not overlook the fact that successful methodologies require competent implementation (or implementation at all) if they are to succeed. Hard research and experience data, rather than engineering judgment, should be the basis of this study.

This task should include a review of available technologies and strive to improve applicability of existing technologies, but should preclude development of new methods. This task should benefit from results of related projects (ATC 1995) and should enhance implementation of those guidelines.

Duration: 3 years

Lead Organizations: FEMA, NSF, Industry

Task 2.4 - Information and Post-Earthquake Studies

A goal of this action plan is to develop the technical information that will result in a performance based seismic design procedure within a period of six years. To achieve this goal, the action plan relies largely on synthesis of existing or easily developed information. While this approach is believed to be adequate for most purposes, clearly additional research on performance based seismic design is desirable to produce the most cost-effective and practical procedures. Subtasks 2.4.1 and 2.4.2 are designed to carry out research in support of performance based seismic design.

No attempt is made to define the details of Subtasks 2.4.1 and 2.4.2. These details should be worked out after initiation of the action plan, at which time the gaps in existing knowledge requiring research will become clearer. The details should be determined by the management group (Task 1.1), the research and practitioner communities, and research funding agencies. Instead of detailed research programs, this task defines two main subtasks. These are (1) to support basic and problem focused technical studies/research in the area of performance based seismic design and (2) to support improved post-earthquake reconnaissance and analysis.

Subtask 2.4.1 - Information Development on Performance Based Design

While the concept of performance based seismic design has been around for many years, its development and implementation have lagged because of the lack of an adequate technical basis. Furthermore, a focused program for developing the technical basis for performance based seismic design did not exist. Although it is possible now to visualize the framework of a performance based seismic design procedure, and within the time frame of this action plan to develop and implement the basic procedure, it is certain that continued technical study and research are needed. The purpose of this subtask is to support continued technical study and research.

The technical studies should be carried out in at least the following areas: Definition of performance criteria and procedures for implementation; procedures for correctly incorporating hazard assessment, risk assessment, and structural reliability; and procedures for structural, geotechnical, and nonstructural analysis and design. Both analytical and experimental procedures should be employed.

The specific details of the required information development will become clearer during the course of this overall project as the tasks targeted for early completion are completed. These studies should be focused on needs identified in this project. To ensure proper focus and coordination, these studies should be directed by or should interact closely with the management group defined in Task 1.1.

Duration: 5 years

Lead Organization: NEHRP Agencies

Subtask 2.4.2 - Integrated Post-Earthquake Studies

Earthquakes that cause damage provide immensely valuable data on the seismic performance of buildings. Current efforts in the United States to collect and evaluate data are under-funded. A national effort to expand post-earthquake studies should include: data collection and analysis of ground motions, and structural and nonstructural performance for damaged and undamaged buildings. The studies should provide in-depth, coordinated evaluations of the collected data, interpretation of the study results for design implementation, recommendations for changes in design codes and standards, and wide dissemination of the conclusions.

Duration: 6 years

Lead Organizations: NEHRP Agencies

Task 2.5 - Develop Guidelines and Commentary for Performance Approach

Previous tasks serve to identify target buildings, key components, target performance levels, indices to relate performance to damage states and to design parameters, and analysis/design methods. These studies are expected to result in improved definition of the targets and methods of performance based design. This information remains to be synthesized to formulate the basis for a new approach to design considering explicitly stated performance goals. The process of preparing guidelines and commentary will help to further identify and fill knowledge gaps. The actual guidelines and commentary will also serve the obvious purpose of setting forth the performance based seismic design approach in unambiguous language.

The skeleton of performance based seismic design should be reliability theory. Reliability theory was used in the 1970s as the basis for the development of load factors and capacity reduction factors upon which the procedures for load resistance and factored design (LRFD) for steel, and strength design for reinforced concrete, are based. Design for explicit seismic performance goals will require implicit or explicit assessment of target reliabilities or safety indices. To date, a comprehensive reliability theory for seismic design has not been developed. The successful implementation of performance based seismic design will require such development. Reliability based design procedures that address the uncertainties associated with ground motion characterization, modeling of framing elements, and use of different analysis tools, will be developed within a decision-making framework naked to all design professionals.

The purpose of Task 2.5 is to formulate basic design and evaluation procedures. To the extent possible, the procedures should be applicable to new or existing buildings, constructed using different types of structural systems and materials, and constructed in various geographical regions of the United States. The procedures should make use of the key ground motion parameters defined in Task 2.3.1. Also, to the extent possible, the methods should be direct so that the underlying assumptions and the relation among input, modeling procedures, response, proportioning and detailing, and performance are easily understood by the competent designer. Guidelines for explicit reliability/safety analysis of structural and nonstructural components should also be prepared (as opposed to including such analysis implicitly in the design and evaluation procedures).

Pertinent issues include (a) identification of when elastic or inelastic analysis methods would be required, (b) the adequacy of equivalent static methods, modal analysis, and response history procedures, (c) establishment of methods for specifying the design earthquakes (forces, displacements, energy, spectral shapes, duration, etc.), (d) setting criteria for accepting analytical models (2D versus 3D, required complexity of overall model, parameter selection for modeling structural and nonstructural components, etc.), and (e) determining appropriate methods for assessing local and global design requirements when performance goals beyond life safety are being considered or when there is a significant difference between the design basis and maximum credible seismic events.

Key to the implementation of performance based seismic design is the development of calibrated prescriptive analysis and design procedures for structural systems that are not conducive to sophisticated analysis because of either modeling (e.g., timber-framed construction) or economic reasons (e.g., residential construction).

The framework of provisions for performance based design should be sufficiently flexible to permit analysis and design using yet-to-be-developed numerical tools and new technologies. To achieve this flexibility, procedures for inclusion of new software and hardware technologies should be formulated.

This task is likely to involve both problem focused studies and a consensus process involving individuals from varied disciplines and geographical interests. Key to the rapid execution of this subtask is the formation of a task group composed of experts in reliability theory and seismic design charged with the development of a framework for reliability-based seismic design. This task group should be formed at an early stage in the project.

This subtask is interwoven with Task 1.7 wherein the publication and dissemination of draft guidelines and commentary after the 25%, 50%, and 75% submittals is described. Early publication of draft versions of the guidelines and commentary is considered key to the rapid implementation of performance based seismic design.

Duration: 4 years

Lead Organizations: FEMA and Industry

Task 2.6 - Develop Benefit/Cost Procedure

The need for alternate performance based seismic design approaches in general, and their selection in specific instances, will rely on procedures being developed for determining the aggregate benefits and costs associated with conventional and performance based approaches. That is, the development of procedures that permit the project team to quantify the relative risk (exposure to loss) of different performance criteria for an owner or client, as compared to construction and other costs incurred to purchase a given level of risk.

The procedures must be able to deal with initial and life cycle costs, must be capable of considering single or multiple buildings as well as single or multiple events, and must account for the uncertainties associated with the earthquake hazard, the building response, and the direct and possibly indirect consequences. While the advantages and disadvantages of benefit-cost methods are in general well understood, only recently have they been applied to the field of seismic design, including building rehabilitation. There are substantial uncertainties in selecting values for the parameters in these methods. These values need to be refined for application to single buildings and groups of buildings located in different seismic regions. Reliability procedures should be used in the formulation of benefit/cost procedures because the performance of buildings (assumed herein to include structural and nonstructural components, and contents) and the consequences of that performance are uncertain.

Procedures for estimating the losses from non-performance of a structure (including nonstructural components and contents) should be developed to permit estimation of actual material risks and societal impacts.

This task involves development of appropriate benefit and cost analysis procedures. The procedures developed under this task will benefit greatly from previous work done under the Benefit/Cost project (FEMA 1992a) and the NIBS Loss Estimation project (NIBS 1994). The final procedures will be used in the verification studies to be carried out under Task 2.7.

Duration: 3 years

Lead Organization: FEMA

Task 2.7 - Verify Design Procedures

There is a need to verify that performance based seismic design methods achieve their objectives practicably and reliably. The response of all components and systems should be verified. Ideally, verification would involve the design and construction of actual buildings, and the gathering of performance data from these buildings subjected to actual earthquakes. Unfortunately (or fortunately), this is not routinely possible. Systematic laboratory experimentation of members, components, and large structural assemblages of building systems may also prove to be infeasible in the short term (though highly desirable in the long term). Instead of the physical approach, computer simulations using validated analytical methods and models may be appropriate. Reliability studies should form an integral part of the verification process.

Not only should the analysis methods be tested to verify that performance objectives are achieved - the studies should also identify the costs and benefits of the performance approach, using the procedures developed in Task 2.6. The benefit/cost studies should (a) determine the costs of designing to various alternate performance levels, (b) determine performance based seismic design standards that achieve target performance levels at least cost, and (c) result in a clearer picture of procedures for achieving the minimum level of acceptable risk.

Subtask 2.7.1 - Evaluate Performance of Buildings Designed to Current Standards

This task involves case studies of target buildings designed using current design approaches. Following design, the performance of the buildings should be studied using the analysis procedures and criteria developed in Tasks 2.1 through 2.6. The task may use actual buildings or buildings designed as part of other trial building design studies.

To adequately evaluate the seismic performance of buildings, including structural framing members, and nonstructural elements and components, comprehensive studies are required. The study should encompass:

- The target building types.
- Design in different geographic regions and for different site conditions.
- Documentation on why design decisions were made.
- Single and multiple buildings and events.
- Performance in terms of the established performance levels.
- Initial and life cycle costs.

All framing systems identified in current seismic codes such as the UBC (ICBO 1994) and the NEHRP Provisions (BSSC 1991) should be studied. (More than forty seismic framing systems are identified in the UBC, although a number of them cannot currently be constructed in regions of high seismicity.) Overall model building types composed of various combinations of framing systems, material, and size will also be considered (FEMA 1992b, ATC 1995). Sample buildings from different seismic regions must be designed (if no designs are available) and analyzed because of regional differences in construction practice and significant differences in the ratios of gravity loads to seismic loads. Buildings located on different soil types must be designed and analyzed; the performance of buildings of one framing system type but of differing heights must also be studied; and the influence of framing regularity (long considered key to building response) must be analyzed in detail.

Consider the number of analyses necessary to characterize the seismic response of buildings with reinforced concrete moment framing systems:

- Number of seismic zones: 5+
- Types of moment frame: 2 (perimeter and distributed)
- Regional practice differences: 1+
- Number of soil types per zone: 4+
- Regularity: 2
- Building heights: 3 minimum (2-, 6-, 10-stories)

Thus, to comprehensively evaluate the performance of one type of seismic framing system, the response of up to 240 buildings should be analyzed for performance at different levels of earthquake shaking, where the characteristics of the earthquake shaking are defined in terms of a probability of exceedance in a given time period. Arguably, more than 1000 analyses per framing system type should be undertaken to comprehensively characterize the behavior of each framing system identified in current codes.

The performance of buildings during seismic shaking should be assessed by teams composed of design professionals, academicians, contractors, and economists (for life cycle cost comparisons). A resource document should be developed that outlines the procedures, mathematical models, software tools, and limit states of response to be used for assessing performance. The assessment of the state of current practice is a key first step in the development of performance based seismic design procedure. Different analysis strategies should be used to investigate response, and the ability of simplified procedures to predict response warrants detailed study.

The duration of this sub-task is set at one year, and timely completion of this sub-task is key to the success of the six-year program. The results of this sub-task will lay the groundwork for the development of performance based seismic design procedures. Strong management and detailed coordination of the work required under this sub-task will be required to ensure success in the allotted time frame.

Duration: 1 year

Lead Organizations: FEMA, NIST, Industry, Design Professional Organizations

Subtask 2.7.2 - Evaluate Performance of Buildings Designed by Performance Procedure

This task involves case studies of target buildings designed using the Guidelines developed in Task 2.5. Following design, the performance of the buildings should be studied using analysis procedures and criteria developed in Tasks 2.1 through 2.6. The target buildings should be the same as those studied under Subtask 2.7.1. Studies and resource document development similar to those described in detail in Subtask 2.7.1 above are proposed to verify the adequacy and efficacy of the performance based design procedures described in Task 2.5.

The cost of this subtask is greater than that of Subtask 2.7.1 because the teams composed of design professionals, academicians, contractors and economists will have to invest time in learning the new performance based design procedures, becoming familiar with new simplified analysis and design tools, and so on. Whereas in Subtask 2.7.1, much of the analytical studies of performance could be based on nonlinear response history analysis (reasonably well understood by many academicians), new procedures developed under Task 2.5 must be used in conjunction with nonlinear response history analysis to estimate the seismic response of framing elements, nonstructural elements, and components.

Duration: 1 year

Lead Organizations: FEMA, NIST, Industry, Design Professional Organizations

Subtask 2.7.3 - Summary Report on Performance Based Seismic Design

This task involves an analysis of the results of Subtasks 2.7.1 and 2.7.2. The objective is to provide closure to the overall program by formulating final recommendations on how to achieve target performance levels and summarizing expected benefits and costs.

Initial findings should be presented and discussed in a workshop, possibly involving architects, structural engineers, geotechnical engineers, geologists, seismologists, buildings officials, insurers, lenders, social scientists, fire protection engineers, emergency response planners, manufacturers of nonstructural products, trade groups of nonstructural component constructors or installers, mechanical engineers, electrical engineers, construction managers, facility managers, health and safety professionals, and building owners. Final results of the study should be forwarded to BSSC and other code-development groups.

Duration: 1 year

Lead Organizations: FEMA, NIST

Schedule Of Work For Element 2

Table 2.1 presents a draft schedule for the tasks of Element 2 of the action plan. The tasks are interwoven with related tasks in Element 1, and should be analyzed in conjunction with the corresponding schedules for those Elements. Logical inter-relations and timing of tasks are described in Chapter 4.

Table 2.1: Draft Schedule for Element 2

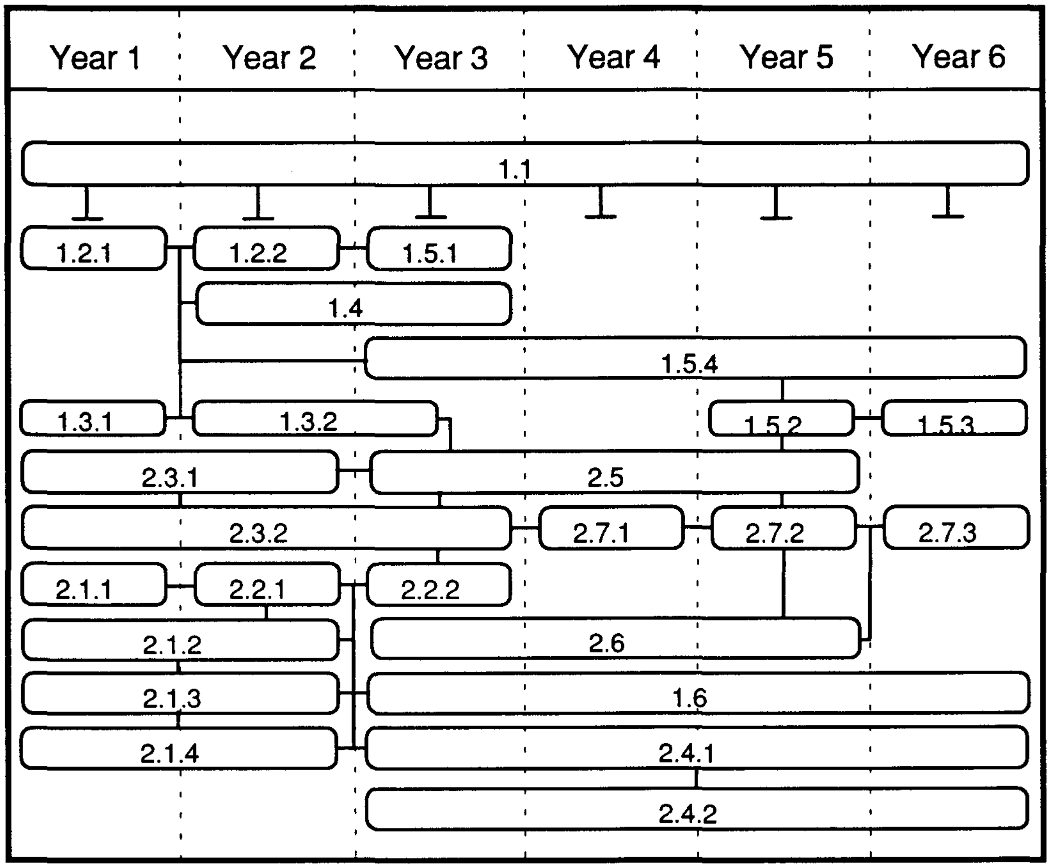
Task	Year											
	1		2		3		4		5		6	
2.1 Inventory/Synthesize Performance Data												
2.1.1 Building contents	■	■										
2.1.2 Nonstructural components	■	■	■	■								
2.1.3 Structural materials and elements	■	■	■	■								
2.1.4 Structural systems	■	■	■	■								
2.2 Relate Parameters to Performance Levels												
2.2.1 Damage to performance			■	■								
2.2.2 Parameters to damage					■	■						
2.3 Evaluate Analysis and Design Methods												
2.3.1 Critical ground motion parameters	■	■	■	■								
2.3.2 Available methods	■	■	■	■	■	■						
2.4 Study Information Needs												
2.4.1 Information development			■	■	■	■	■	■	■	■		
2.4.2 Post-earthquake studies	■	■	■	■	■	■	■	■	■	■	■	■
2.5 Develop A/D Guidelines					■	■	■	■	■	■	■	■
2.6 Develop Benefit-Cost Procedures					■	■	■	■	■	■		
2.7 Verify Design Procedures												
2.7.1 Evaluate current procedures							■	■				
2.7.2 Evaluate new procedures									■	■		
2.7.3 Summary report											■	■

Chapter 4

RECOMMENDED SEQUENCE OF TASKS

Chapters 2 and 3 describe a total of 26 tasks or subtasks that compose Elements 1 and 2 of this action plan. Several of the tasks are linked with other tasks, either requiring data from a preceding task, providing data to a subsequent task, or interacting with a concurrent task. The schedules for both Elements result in a logical sequence of tasks. Should it become necessary to deviate from those schedules, it will still be necessary to carry out the tasks in a logical sequence. The chart on the next page indicates the sequential relation among the various tasks.

Sequential Relation Among Tasks and Subtasks



Key: 1. Number in each box refers to the Task number.

2. Lines connecting boxes indicate recommended work sequence.

3. Concurrent tasks are indicated by lines connecting between top and bottom edges of adjacent boxes.

Chapter 5

RECOMMENDATIONS FOR EARLY ACTION

Several tasks contained in the action plan lay the foundation for the overall project, and must begin as soon as practical. The following tasks are recommended for early action by the funding agencies.

- Establish the management group (Task 1.1);
- Identify possible users of alternate performance levels and performance based design procedures (Subtask 1.2.1);
- Inventory currently available specifications for building components and identify components and systems without specifications (Subtask 1.3.1);
- Inventory and synthesize performance data on building contents, nonstructural components, structural materials and elements, and structural systems (Task 2.1);
- Evaluate analysis and design methods (Task 2.3);
- Develop an integrated post-earthquake studies program (Subtask 2.4.2).

The first-year cost of these tasks is estimated to be $2,950,000.

Chapter 6

REFERENCES

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Appendix A

PROGRAM BENEFITS AND COSTS

There are considerable benefits that will result from the effort described in this action plan. A primary benefit of the development of seismic design procedures will be improved reliabilities in our building stock, which will result in reduced building damage and improved functionality of buildings during and after an earthquake. Approximately $450 billion in construction work is undertaken each year in the United States; even a small percentage reduction in earthquake losses will equate to huge dollar savings. (Based on current California Office of Emergency Services estimates, the total Northridge earthquake loss is from 5% to 10% of the national annual construction expenditure.) Furthermore, because the effort will result in improved understanding of building performance, designers will be able to make more efficient use of building materials to achieve a given performance goal.

The United States government owns 417,000 buildings totaling 2.8 billion square feet, with a replacement cost of $276 billion. In addition, 218 million square feet are leased, and 3 million federal employees work in these federally owned and leased facilities (GAO 1992). Non-federal property loss exposure is many times greater; for example, the values of buildings in Los Angeles County is about the same as that of the total federally-owned building stock in the United States (Scawthorn and Gates 1983). Reductions in direct and indirect earthquake losses, and possible reductions in construction costs, will be a significant direct benefit to the United States. Furthermore, since many of these buildings house functions critical to defense facilities and key industries, improved seismic reliabilities will enhance national security.

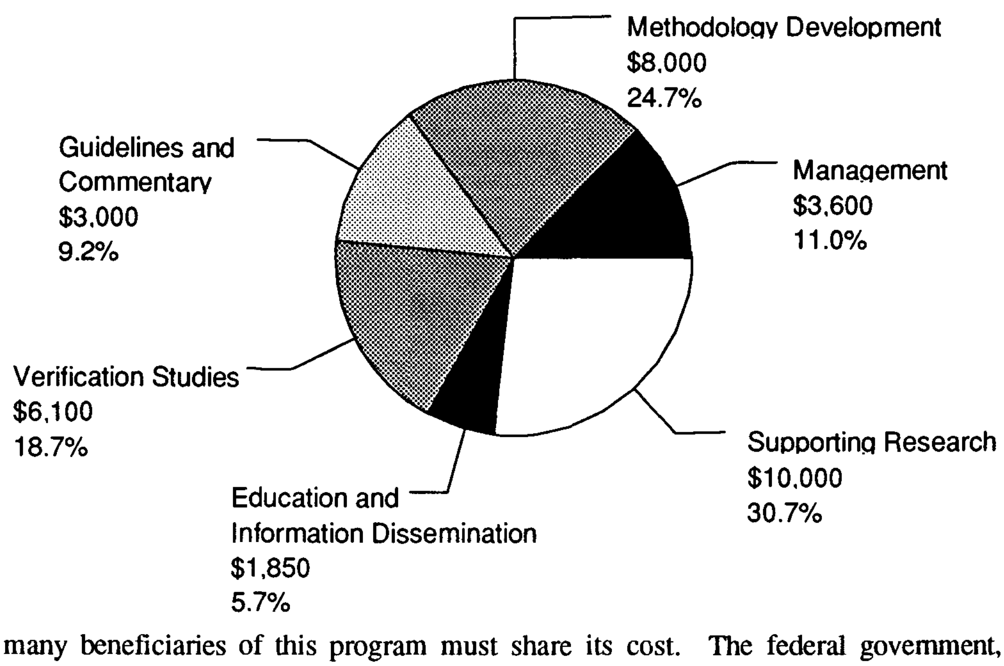
The effort described in this action plan will benefit individual states and private companies. Relocation of industry and operations from one state to another to avoid the direct and indirect costs associated with earthquakes involves considerable expense and employee disruption, and reduces the tax base for the state and the community from which relocation occurs. Given an adequate understanding of the relation between building design and building performance, the money could be better spent on building improvements to achieve enhanced performance. This study on performance based seismic design and the resultant guidelines will produce that understanding.

Finally, this study will result in improved international competitiveness for United States firms. The performance based seismic design procedures will apply to different seismic hazard levels, various building construction forms and materials, and a range of performance levels. Therefore, the procedures will be applicable anywhere in the United States and will be exportable to other countries.

While there are net long-term benefits in performance based seismic design, there are short-term costs associated with achieving the goal. The total cost for the effort represented in this action plan is $32.55 million spread over a six-year period. While this is a substantial sum, it should be recognized that this sum is a minute fraction (less than 0.01%) of the total annual construction expenditure (approximately $450 billion) in the United States, and a small fraction of the losses commonly associated with a moderate or severe earthquake in an urban area.

The chart below indicates an approximate breakdown of estimated cost to complete the program described in the action plan.

Cost Breakdown
(in thousands of dollars)



The many beneficiaries of this program must share its cost. The federal government, through FEMA, which initiated this study, should be expected to provide the necessary resources for the first-year startup tasks (see Chapter 6), as well as some of the other tasks. Once the program is initiated, a key responsibility for the program management group (see Task 1.1 in Chapter 2) will be to develop continued funding from the various federal, state, and private funding entities. Agencies commonly involved in funding guidelines development and trial designs include DOD, DOE, FEMA, GSA, NIST, USPS, and VA, while those commonly involved in funding research include NSF and USGS. Matching funds from private sources including lending, insurance, and materials industries also should be sought so that a public-private partnership supports this program.

The draft summaries of estimated costs for Elements 1 and 2 are detailed in Tables A.1 and A.2 below. A summary of the draft budget for the execution of the Action Plan is presented in Table A.3. The cost estimates below include equipment, overhead, and related incidental costs.

Table A.1: Summary Budget Estimate for Execution of Element 1

		Estimated Cost ($1000)						
		Year						
Task	Subtask	1	2	3	4	5	6	Total
1.1		200	500	700	700	700	500	3300
1.2	1.2.1	350	---	---	---	---	---	350
	1.2.2	---	250	---	---	---	---	250
1.3	1.3.1	150	---	---	---	---	---	150
	1.3.2	---	200	100	---	---	---	300
1.4		---	100	100	---	---	---	200
1.5	1.5.1	---	---	250	---	---	---	250
	1.5.2	---	---	---	300	---	---	300
	1.5.3	---	---	---	---	200	200	400
	1.5.4	---	---	125	125	125	125	500
1.6				100	100	100	100	400
1.7			100	100	---	100	200	500
TOTAL COSTS		700	1050	1475	1225	1225	1225	6900

Table A.2: Summary Budget Estimate for Execution of Element 2

		Estimated Cost ($1,000)						
		Year						
Task	Subtask	1	2	3	4	5	6	Total
2.1	2.1.1	200	---	---	---	---	---	200
	2.1.2	500	500	---	---	---	---	1000
	2.1.3	700	700	---	---	---	---	1400
	2.1.4	250	250	---	---	---	---	500
2.2	2.2.1	---	250	---	---	---	---	250
	2.2.2	---	---	1500	---	---	---	1500
2.3	2.3.1	150	100	---	---	---	---	250
	2.3.2	200	400	400	---	---	---	1000
2.4	2.4.1	---	2000	3000	2000	1000		8000
	2.4.2	250	500	500	250	250	250	2000
2.5	--	---	---	500	1000	1000	500	3000
2.6	--	---	---	150	150	150	---	450
2.7	2.7.1	---	---	---	2500	---	---	2500
	2.7.2	---	---	---	---	3500	---	3500
	2.7.3	---	---	---	---	---	100	500
TOTAL COSTS		2250	4700	6050	5900	5900	850	25650

Table A.3: Summary Budget Estimate for Execution of the Action Plan

	Estimated Cost ($1,000)						
	Year						
Element	1	2	3	4	5	6	Total
1 Planning, policy, and implementation	700	1050	1475	1225	1225	1225	6900
2 Technical and design issues	2250	4700	6050	5900	5900	850	25650
TOTAL COSTS	2950	5750	7525	7125	7125	2075	32550

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ISSUE PAPER #1

Issues in Defining Performance Criteria

by

Ronald O. Hamburger

1. Issues in Defining Performance Criteria

1.1 Introduction

A performance based design procedure should ideally start with the specification of desired performance objectives for the structure, given the hazard environment in which it is to be constructed and then provide a direct, rational path by which the structure may be designed to attain these goals. In addition to providing the steps for a performance based design, such a procedure should ideally permit backwards evaluation of an existing structure's probable performance when subjected to an event of specified severity.

Current building code procedures for seismic resistive design purport to be performance based. The commentary to the SEAOC provisions[1] states three qualitative performance goals for different levels of earthquakes, ranging from property protection in minor events to protection of life safety for an ambiguously defined major event. The UBC[2], which incorporates many of the SEAOC recommendations implies that it provides appropriate design for multiple performance goals, in that special criteria are provided for the design of emergency response facilities and buildings containing hazardous materials. The implication is that facilities so designed will provide post-earthquake functionality and containment of hazardous materials. Similarly, the NEHRP Provisions[3] define a number of building performance categories, based on occupancy and site seismicity, which in turn control levels of detailing incorporated into the design.

In recent years, structural engineers have increasingly expressed the opinion that these codes are not truly performance based. They do not really allow the designer to specify multiple target levels of damage for given design events and then proceed by rational means to produce a structure which is capable of meeting these goals within a defined level of reliability. Further, the primary performance goal of protecting *life safety* may not be adequately provided for in zones of moderate seismicity. Current design procedures for these zones allow brittle detailing practice coupled with ground motion demands substantially lower than those which could credibly occur, potentially resulting in buildings with inadequate margin. Finally, current procedures do not provide a tool by which the probable performance of a structure of known construction can reliably be judged. This paper explores issues relating to definition of performance objectives and suggests areas where additional research may be required as part of the development of a true performance based code.

Table 1-1 summarizes all the issues in this paper.

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[1]Structural Engineers Association of California. "Recommended Lateral Force Procedure and Commentary" 1990. San Francisco, CA

[2]International Conference of Building Officials. "Uniform Building Code" 1991. Whittier, Ca

[3]Building Seismic Safety Council. "NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings". Federal Emergency Management Agency. 1991. Washington, DC.

Table 1-1: Summary of Issues in Defining Performance Criteria

1.1 Basis for Performance Goal Definition: Should goals be based on performance in specific events, an integrated probability of failure, or other measure?

1.2 Alternative Performance Considerations: What considerations should be incorporated in performance goals included in design procedures?

1.3 Minimum Performance Goals: What are appropriate minimum performance goals?

1.4 Relating Performance Goals to Damage States: What are the limiting levels of damage and the corresponding parameters which define a performance goal?

Issue 1.1: Basis for Performance Goal Definition

Issue Statement

Should goals be based on performance in specific events, an integrated probability of failure, or other measure?

Background

Performance goals may be defined in different ways. Current codes adopt a *single event* approach. A single goal, typically *life safety,* is tied to a single hazard level. Commonly, a 500 year event is used as the basis for design. It is implied that margins of safety provided are adequate to make earthquake induced collapse in any credible event, unlikely. However, hazard studies for many regions indicate that structural demands produced by a 500 year event are a relatively small fraction of those which occur less frequently, yet are credible. There is no consensus that adequate margin exists in the design procedures to maintain the risk of earthquake induced collapse at a suitably low level. Further, there is no way of directly understanding the risk of lower levels of damage resulting in potential economic loss or business interruption, among other performance concerns.

Multi-event approaches reduce these problems. The armed services adopted a two-level approach[4]. Structural designs are checked against two sets of capacity parameters, for different earthquake demand levels, each tied to different performance goals. Performance is checked both for frequent events, producing moderate demands, and infrequent events representing the most severe conditions ever likely. Goals range from immediate building re-occupancy to prevention of collapse, depending on building occupancy and mission. Alternative approaches using a greater number of event levels, could also be developed. Multi-event approaches are clearly more

[4]Departments of the Army, Navy and Air Force. "Technical Manual - Seismic Design Guidelines for Essential Buildings TM-5-809-10-2; P-355.2; AFM-88-3, Chap 13 Sec. A" 1986. Washington, DC.

performance based then the single event procedures of current codes, however, appropriate hazard levels must be selected for the various events. If for example, immediate post-earthquake occupancy is required for a building in "probable" events - the term probable must be tied to a specific hazard level, for example recurrence intervals of 50, 100, 150, or other interval of years. The selection of these hazard levels is currently made on an arbitrary basis.

Segments of the nuclear industry take a *probabilistic* rather than event based approach to performance definition. Rather than specifying that a performance goal, such as *hazardous material confinement*, be tied to a specific hazard level, procedures developed by the Department of Energy[5] define an annual probability of failure to attain the desired performance goal. Thus performance goals may be stated in a format such as a 10^{-5} annual probability that earthquakes would result in damage severe enough to cause hazardous materials release. Goals defined in this manner have the ability to account for the conditional probability of failure at all levels of earthquake demand which may affect the structure, integrated with the probability that the demand actually occurs. The benefit of this approach is that the actual risk level selected as the basis of design is clearly stated and can be achieved uniformly in all regions, regardless of seismicity. However, given current technology, there is no direct way to design for such performance objectives. Rather, a design must first be developed, and then evaluated, using methods of reliability theory, to determine the expected failure rate. Structural reliability methods are not well known in the design professions, can not currently be performed on a routine basis, and may be of questionable accuracy for complex systems. Even the design procedures currently adopted by the nuclear industry typically tend to be multiple-event procedures, with the events selected based on expert opinion and judgment, with the intent being to achieve the implied reliability levels.

Alternatives

1. Design procedures should continue to be based on single events, as procedures using multiple levels, or requiring evaluation of reliabilities are too complex for practical application.

2. Design procedures should be based on multiple levels of performance and events, as the single event approach may not provide acceptable performance in events which are either much smaller or much larger than the target level.

3. Design procedures should specify a single event for basic design to minimum standards, but should provide procedures for evaluation of performance at other levels of event for use when desired.

4. Design procedures should incorporate reliability analysis and be based on an integrated risk of failure to achieve goals, as this is the only valid basis for judging whether a design is acceptable either economically or from a perspective of risk.

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[5]Department of Energy. "Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards" University of California - Lawrence Livermore National Laboratory - UCRL-15910. 1992.

5. Design procedures should be based on either single or multiple events, but with the design events selected based on reliability theory and a target expectation of risk that the structure would ever fail to achieve the performance goals.

Recommendation

Alternative 5 is recommended. The scope of research and technical studies for this issue should include:

a. Identification of appropriate levels of risk of building collapse, life loss, economic loss and other losses, which may be recommended as a basis for design.

b. Identification of the appropriate number of events, hazard levels for each design event, and margins of safety for acceptance criteria for each event, required to achieve these target risk levels.

c. Development and promulgation of simplified methods of reliability analysis which engineers may use to evaluate the risks inherent in their designs.

Issue 1.2: Alternative Performance Considerations

Issue Statement

What considerations should be incorporated in performance goals included in design procedures?

Background

It is necessary to define the performance goals which are to be achieved by the structure. A performance goal is a statement of a limiting damage state, which will be exceeded with a defined probability, given either a single demand or probabilistic distribution of demands. Current codes are based on a *substantial life safety* goal. This implies design such that the risk of damage resulting either in collapse or falling hazards capable of causing severe injury is very low. Sometimes this also requires protection of building egress including stairways and corridors such that people may leave the structure following the event. In the limiting state for this goal, buildings are permitted to have substantial damage and failure of both structural and non-structural components, so long as life safety is not jeopardized. Buildings meeting this goal may be total economic losses. This goal is typically adopted as the minimum code standard, in the name of protecting the public welfare.

Some current codes also attempt to address *immediate post-earthquake occupancy* as a goal. This goal assumes minimal structural damage and limited damage to non-structural components. The intent is that the building is as safe to occupy following the earthquake as it was before. People may continue to inhabit the structure in safety even though aftershocks are likely to occur. Current codes specify this goal for buildings housing functions critical to post-earthquake recovery including hospitals, emergency operations centers and similar facilities, again in the interests of the public welfare. The immediate post-earthquake occupancy goal does not ensure functionality. In addition to the limits on structural and component damage required for post-earthquake occupancy, *post-earthquake functionality* may require that mechanical and electrical services be operable following the earthquake. This is typically beyond the scope of most current codes, with the exception of standards adopted by the nuclear industry for critical safety related systems. In addition to structural considerations, design for this goal may require provision of alternative stand-by supplies for critical utilities and rigorous qualification of electro-mechanical components to ensure they retain their operability when subjected to expected shaking.

A *hazardous material containment* goal is also addressed by some current procedures. Process, power, semiconductor, waste and other industries all maintain stores of materials, within buildings and structures, which should not be permitted to escape in quantity. To achieve this goal, structural degradation of containment structures must be maintained at very low levels.

A *building conservation* goal is desired by some segments of society. The goal of building conservation is to limit damage to an extent which would permit the building to be repairable. This may be sought for buildings which are culturally or historically significant and which can not be practically replaced with a reconstructed structure.

A related goal is *specified economic loss*. Financial institutions are concerned with probable post-earthquake repair costs. Increasingly, probable maximum loss (PML), an expression of probable post-earthquake restoration cost, is used as an acceptability index by lenders and underwriters. Protection of the public welfare, may include economic as well as safety considerations. Increasingly society demands that codes minimize the risk of catastrophic economic loss.

Occupancy interruption is also an important concern. Individual owners and tenants can afford some loss of use, following a major disaster and few can afford design for immediate occupancy following a major event. However, long term loss of use of a large portion of a region's building stock, following a disaster, can result in unacceptable economic and health impacts on the region. Damage control, to an extent that long term loss of use in a large portion of a region's building stock does not occur, may also be an issue of public welfare.

Alternatives

1. Design procedures should continue to have a single life safety performance objective as this is the only goal which a code can legally enforce.

2. Design procedures should be based on a performance objective which balances considerations of risk to life safety, potential loss of use of building stock, and economic factors as all of these are critical to protecting the public welfare and can be incorporated in codes.

3. Owners should be permitted to select custom design performance objectives based on one or more of the above (life safety, hazardous materials confinement, immediate occupancy, building conservation, economic loss and occupancy interruption), as suited to their individual requirements.

4. Design procedures should provide a minimum performance objective, based on considerations of life safety as well as economic factors, but should also provide methods by which higher

performance objectives (hazardous materials confinement, immediate occupancy, building conservation, economic loss control, and occupancy interruption) can be designed for.

5. Design procedures should provide minimum performance objectives, appropriate to specific occupancies, with additional procedures provided to meet higher performance objectives (hazardous materials confinement, immediate occupancy, building conservation, economic loss control, and occupancy interruption) when owners desire these.

Recommendation

Alternative 5 is recommended. The scope of research and technical studies for this issue should include:

a. Quantification of the relationship between building restoration costs and earthquake severity as a function of building capacity and stiffness.

b. Quantification of the relationship between time to restore buildings to service and earthquake severity as a function of building capacity and stiffness.

c. Quantification of the damage levels at which building restoration to service becomes impractical, for both landmark and common structures.

Issue 1.3: Minimum Performance Goals

Issue Statement

What are appropriate minimum performance goals?

Background

Current codes adopt *life safety* goals for most normal occupancy buildings, and *immediate occupancy* goals for buildings which are deemed critical to society. These goals have generally been adopted based on the concept that it is government's duty to protect the public safety and welfare. However, the reliability with which current procedures can attain these goals is not well defined. Further, considerations of cultural and economic loss, either to individuals or society, have largely been ignored by these design procedures. Recently, segments of the community have expressed concern that the basic goals of current design procedures may not be optimal.

Studies conducted by the Department of Energy[6] have estimated that current design procedures result in building designs with a 10^{-3} annual probability of failure to meet their performance goals. Given that the typical design event has a 500 year expected recurrence interval, or an annual probability of exceedence of $2x10^{-3}$, this indicates a significant probability of life threatening failure of buildings when subjected to large events. If these reliability estimates are accurate, few

[6]Department of Energy. "Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards" University of California - Lawrence Livermore National Laboratory - UCRL-15910. 1992.

engineers or building officials are likely to find this to represent an acceptable risk for life safety. However, these reliability levels may be quite acceptable for goals other than life safety, so long as the owner of the building understands the risks involved when commissioning the building design.

Following the Loma Prieta Earthquake, government became concerned with the potential economic cost of large earthquakes. The $7 billion dollar direct loss caused by this event was only moderately insured and economic recession throughout Northern California followed. The concept that design codes should more closely and directly consider control of property loss was introduced and given greater credibility by the lack of confidence prevalent in the insurance industry following large losses experienced in the earthquake as well as a series of hurricanes affecting other regions.

Designing for increased reliability and for reduced losses in future earthquakes will result in a direct increase in initial construction costs. The cost benefit curve for seismic resistance is like that for most reliability issues. Initial investments in seismic reliability provide relatively large returns in improved reliability and reduced maintenance and repair costs over the life of the building stock. As initial investment continues to increase, incremental returns are reduced. At some point, the incremental cost of providing additional seismic reliability is balanced by declines in expected future costs including repair and reconstruction, and business interruption such that a minimum life cycle cost is obtained. This point may or may not represent an acceptable level of risk with regard to life safety or other issues.

Alternatives

1. A single standard for all buildings based on a defined low risk of life safety endangerment should continue to be the minimum goal of the code.

2. In addition to the single goal of alternate 1, a goal of immediate occupancy with a defined reliability rate, should be adopted for certain buildings in critical public service.

3. In addition to the goals of alternates 1 and 2, the minimum performance goal should be adjusted to provide for minimum life cycle cost of earthquake safety, considering a region's building stock as whole.

4. Owner's should be permitted to select their own performance goals without constraint to a minimum standard.

Recommendation

Alternative 3 is recommended. The scope of research and technical studies for this issue should include:

a. Evaluation of the cost-benefit relationships for improving seismic reliability for different classes of buildings and in regions of different seismicity.

b. Evaluation of appropriate target levels of reliability for life safety.

c. Evaluation of appropriate target levels of reliability for immediate occupancy for critical public service facilities.

Issue 1.4: Relating Performance Goals to Damage States

Issue Statement

What are the limiting levels of damage and the corresponding parameters which define a performance goal?

Background

A building is comprised of a number of systems and components. Structurally, there are at least two such systems - the vertical and lateral load resisting systems. In addition to the structural systems, there are mechanical, electrical, curtain wall, ceiling, and many other types of systems present. Traditionally, earthquake resistive design procedures have focused attention on only one of the structural systems -the lateral system, while largely neglecting the other systems, except on an individual component basis. However, the damage sustained by each of the systems in the building is an important determinator of the building's overall performance, particularly with regard to issues of business interruption and repair cost, but also in regard to life safety.

It is obvious that if a structural system in a building is damaged and looses stability, the building will fail to meet a life safety performance goal. However, damage to other systems can also result in life safety hazards. Curtain walls are an obvious system, the failure of which has life safety consequences. Failure of mechanical and electrical systems can result in release of life threatening materials, ignition of fires, and a loss of automated fire protection, all of which can have life safety implications.

Post-earthquake building occupancy is clearly dependent on the performance of the non-structural systems as well as the structural ones. For a building to be safe for occupancy, it must not only be structurally safe, but must also have electric power for lighting and function of elevators. In some buildings, climates and occupancies, mechanical heating, ventilating and cooling systems are also required.

The cost of damage resulting to a building in an earthquake is often more a function of damage to the non-structural systems than the structural ones. Damage to fire sprinklers and resulting water damage to architectural finishes and furnishings have been a significant part of repair costs in a number of buildings which had relatively minor structural damage. In the recent Guam earthquake, a major component of repair costs related to the restoration of cracked ceramic tile walls in bathrooms of guest suites in a number of high-rise hotels. Current design procedures do not adequately provide for protection of buildings against such losses.

Current design procedures for both structural and non-structural components focus first on force delivered to a component, second on the amount of deformation the component will experience, and third on the manner in which the component is constructed or detailed. Component behavior is viewed in a "switched" mode, where something is either damaged or not. Although a relationship clearly exists, there is little definitive correlation available between the parameters actually used in design, i.e. force, deformation and detailing, and the performance of the individual components. Neither has the importance of other parameters including velocity, frequency content or duration of excitation been explored or fully accounted for in the design procedures.

The state in which a building exists following response to an earthquake is a composite of the states of all of the systems which comprise the building. For each performance goal, the extent to which each of the systems can be permitted to be damaged requires quantification. If design procedures are to be performance based, the design parameters which influence the performance of all of the systems which comprise the building must be identified and suitable acceptance criteria developed.

Alternatives

1. Structural engineers should indicate to the other design professionals engaged in the building design, the seismic environment which will be produced by the structure's response to a design earthquake and it should be the responsibility of the other professionals to design their systems to accommodate this environment.

2. Force and drift as contained in current design procedures are the best parameters to control building performance and should remain as the primary parameters used for design as these can be readily calculated and have a demonstrated relationship to building performance.

3. As earthquakes being a dynamic phenomena, the design of all building systems and components should be based on considerations of the dynamic response of the component to its environment as predicted by floor response spectra and similar tools.

4. For each performance goal, a comprehensive listing of target component behavior at different earthquake severity levels should be used to develop appropriate acceptance criteria for design purposes for both structural and non-structural systems.

Recommendation

Alternative 3 is recommended. The scope of research and technical studies for this issue should include:

a. Identification, for all major structural and non-structural components which are important to building performance, of the key parameters (displacement, velocity, acceleration, force, duration, frequency content, etc.) which affect performance.

b. Identification, for all major structural and non-structural components which are important to building performance, of the levels of damage permissible at various earthquake severity levels to achieve specified performance goals and of the limiting acceptable values of the design parameters to achieve these performance levels for the important components.

ISSUE PAPER #2

Format, Enforcement, and Implementation

by

Christopher Arnold

2. Format, Enforcement and Implementation

2.1 Introduction

The related issues of format, enforcement and implementation might be seen as peripheral to the critical technical issues in establishing a methodology for the practice and regulation of performance-based design, but ultimately these non-technical issues will determine the success or failure of the new methodology.

Implied in this methodology is an explicit way of relating engineering design to anticipated building performance, which would be reflected in design guidelines and code provisions. In doing this, some of the traditional format of our building codes will be called into question. Current codes presume a knowledge of design and focus only on mandatory criteria and prescriptive design requirements related to an undefined performance level. No philosophy of design or performance expectation is explicitly addressed. The new code would define alternative performance objectives and provide the criteria for achieving them, within a new framework of seismic analysis and design.

The definition of criteria for several levels of design and performance will make enforcement a more complex procedure than it is today, in which conformance to only one level of analysis and prescriptive requirements must be established.

Since a new design philosophy will be embodied in the code, implementation will require the development of implementation strategies to ensure that all those affected understand the rationale, benefits and limitations of the proposed approach. The ultimate decision for code adoption will be made not by the engineers who devise the code but by elected officials acting in response to the public will, expressed in hearings, private comments and the press.

A general issue in respect of performance-based seismic design needs to be stressed: that, from the public's view point, performance based design will be seen as being proposed because engineers *cannot provide the performance that the public expects and are attempting to negotiate an acceptable compromise*. The public expects that a properly enforced building code will provide almost complete protection from structural failure, as is the fact with structural provisions for vertical forces. A serious design or construction error must occur for a vertical force failure to be life-threatening.

Performance-based seismic design aims to make explicit a fact that has not been emphasized by the structural community until recent events have forced it to do so: that adherence to seismic codes and good seismic design not only do not preclude building damage, but our current design methodologies to some extent depend on it. To the public, ductile behavior is damage. A performance-based seismic code seeks to make explicit the amount and types of *damage to be expected* - though the expectation may not, necessarily, be expressed in those terms. There is a need for particular clarity of exposition and delicacy in the language by which this new design philosophy is explained to the public.

Table 2-1: Summary of Format, Enforcement and Implementation Issues:

2.1 **Format:** What is the appropriate format for a performance-based seismic code?

2.2 **Implementation Strategies:** What strategies should be used to expedite the implementation of a performance-based seismic code?

2.3 **Training and Information Exchange:** What education, training and information exchange is necessary to ensure proper application and enforcement of a performance-based seismic code?

2.4 **Communications among the Project Team:** What are the implications of a performance-based seismic code on the needs for communication between the owner and the design and construction team?

2.5 **Liability Issues:** What liability issues might arise if a performance-based seismic code is implemented?

Issue 2.1: Format

Issue Statement

What is the appropriate format for a performance-based seismic code?

Background

Format refers to the scope, language and layout of a document. Any format has a direct relationship to intent and audience: for example the need for enforcement mandates the precise unambiguous language of the typical code. The legal basis of codes does not allow their scope to include explanation and conceptual discussion. The code presumes a background of knowledge and design skill.

While the traditional format of a code is familiar, recent FEMA documents have taken the form of "Provisions", "Commentary" and "Guidelines." Some discussion of these terms is necessary.

Considerable emphasis has always been placed on the fact that the *NEHRP Provisions* is a "resource document" rather than a code, and it is assumed that a FEMA effort for performance - based design would be directed towards a resource document rather than a code. While this may be so, the language of the *NEHRP Provisions* is that of conventional code language. For example, compare these two clauses, dealing with the same requirement, in the UBC (Code) and the NEHRP Provisions (Resource):

UBC: "**Sec. 2334.**(g) **Overturning.** 1. **General.** Every structure shall be designed to resist the overturning effects caused by earthquake forces specified in Section 2334(d)."

NEHRP: "**4.5 Overturning**: The building shall be designed to resist overturning effects caused by the seismic forces determined in Section 4.3."

In the UBC each clause is titled a "Section": in the *NEHRP Provisions* each clause is given only a numerical designation, but are generally referred to in the text as "sections".

The *NEHRP Provisions* are accompanied by a *"Commentary"* in a separate volume, that provides background and discussion on each section of the document, and some discussion of broader philosophical issues, which vary from chapter to chapter. The SEAOC "Blue Book" provides a commentary that performs a similar function for the UBC.

The "Guidelines" document as currently under development for the FEMA "Guidelines for the Seismic Rehabilitation of Buildings" project is approximately equivalent to the *"Provisions"* volume of the *NEHRP Provisions*. These Guidelines are to be accompanied by a Commentary equivalent to the *"Commentary"* volume of the *NEHRP Provisions.*

Successful implementation of a new technology or technically based process, is generally matched by a progression in the type of documentation that is provided and the language in which it is written: the *code* comes at the end of this progression. Study of the documentation of a new technology such as base-isolation demonstrates this. When base-isolation first became feasible for practice, documentation focused on providing engineers with understanding of the basic concepts. This was followed by "guidelines' and handbooks to assist the engineer in design. Such documentation was also aimed at building officials, because at this time no codes had been written or adopted for the technique. Implementation of a few projects under special provisions of the building codes that allowed for innovative analysis and design techniques was followed by the development of a proposed model code which appears (in the SEAOC "Blue Book") as an appendix. Ultimately, these provisions will move into the body of the code.

This progression perhaps provides a model for document format, and also for the implementation process itself, which is discussed in Issue 2.2 below. The progression might start with the production of a set of "Guidelines" that express the philosophy and approach of the new methodology. This would set a context for the development of a set of "Provisions" and "Commentary" as technical resource documents. Model code groups would then adapt the provisions for incorporation into a model code.

Alternatives

1. The FEMA effort should be confined to producing a set of *"Guidelines"*, and model code groups should handle the development of *"Provisions"* and their incorporation in a model code

2. *"Provisions"* should be developed, together with a *"Commentary"* that is closely related to each section and provides background information on its rationale.

3. The FEMA effort should produce a set of *"Guidelines"* which would discuss the general philosophy and approach of performance-based design. This would be written in language and style accessible to all technical participants in the design process: architects, engineers, and building officials. A FEMA team would then develop a set of *"Provisions"* that model code groups could convert into a model code, and a *"Commentary"* that would provide technical background information on the rationale for each section.

Recommendation

Alternative 3 is recommended. Work should be done on determining the scope of the Guidelines, Provisions and Commentary and establishing language, style and format that can guide both the writing and thinking of participants as the technical studies proceed.

Issue 2.2: Implementation Strategies

Issue Statement

What strategies should be used to expedite the implementation of a performance-based seismic code?

Background

Normal code development has a well worked out process for the modification and augmentation of a code. This has tended to be a process of accretion: as a problem is discovered in the field, or a material or design innovation surfaces, provisions are added to the code. This process results in an unwieldy code: and the lack of an overall context for the code makes it difficult to accept large-scale conceptual innovations.

A proposed performance-based seismic code will represent a fundamental re-thinking of the conceptual basis of seismic design and consequent regulatory expression. As such, it may be argued that such an innovation is best accomplished by complete replacement of the existing code document, leaving the way open for a fresh conceptually effective start.

One successful precedent for the introduction of an entire new code into the building process was that of the development and implementation of energy codes following the energy crisis of the early 70s. However, this process had some characteristics that made energy code implementation much easier than that of a new seismic code:

1. The code had governmental backing at the highest level.

2. Life safety was not an issue.

3. The energy code did not replace or modify an existing code or threaten existing constituencies.

4. Although additional costs were associated with the code, it could be convincingly shown that implementation of the code would provide cost savings (often considerable) in building operation.

5. Calibration of costs and benefits could relatively easily be accomplished.

6. Implementation of the code did not require education of existing inspectors and building officials : a new group of officials or consultants assumed this role.

However, it is not yet clear how much of a current code needs to be replaced in a performance-based code. It is possible to conceive that performance-based provisions would be responding to a particular set of problems in our present codes, but that wholesale replacement of the code would not be necessary. For example, much of the materials section in present codes might remain. To the extent that code change can be evolutionary rather than revolutionary it would be advantageous for the expeditious implementation of the new code. The wholesale replacement of a code calls into question the whole basis of previous code development and raises problems for the host of non-conforming structures that would be created.

The "progressive" model of documentation discussed above in Issue 2.1 suggests that a similar incremental approach might be used to advantage in the planning the implementation of a performance-based code. For example, it seems unlikely that all parts of the code could equally easily be developed simultaneously to a consensus level. Some building types have more predictable behavior than others, based on calibration of analysis with known behavior in earthquakes. Similarly, the ground motion shaking can much more easily be characterized in some regions rather than others.

Thus it would appear beneficial to explore the possibility of an incremental strategy relating to building types, structural systems, materials and earthquake hazard with a procedure for introducing them into the code when the technical problems have been worked out and clear statements can be made about benefits, costs and social and political implications. The idea is a strategy by which the code evolves over time into a new code, rather than an attempt at instant replacement. With this strategy it is not necessary to wait until solutions for all structural and risk conditions are satisfied, nor is it necessary to draw undue attention to some significant evolutions in the code. However, this strategy must also recognize that some of the changes introduced into the code would represent major conceptual and philosophical shifts, and that this approach would go well beyond the current incremental approach to code modification.

Alternatives

1. Wait until a new code can be perfected and then work to implement it with a planned "campaign" supported by appropriate publications and activities.

2. Attempt to implement new provisions into the existing code in an incremental way, and provide appropriate explanatory materials and activities to accompany the proposed changes..

3. Develop a progressive strategy, starting early on with documents and activities to explain and obtain guidance on the philosophical basis behind proposed changes, and then implement new provisions into the existing code in an incremental way.

Recommendation

Alternative 3 is recommended. A study should be initiated to make a preliminary determination of which sections of the current Provisions will need to be replaced, and which might remain or need only minor modification comparable to a typical three-yearly update. Based on this study, a determination should be made as to the extent to which a progressive strategy is feasible, and the steps of such a strategy be laid out.

Issue 2.3: Training and Information Transfer

Issue Statement

What education, training and information exchange is necessary to ensure proper application and enforcement of a performance-based seismic code?

Background

Once a new, or augmented code is in existence, technical personnel concerned with its use must be familiarized with its provisions. For the modifications that occur every three years in the current code, it is not hard for experienced designers and building officials to acquaint themselves with the changes and incorporate them into their design or checking process.
Goals and objectives are currently outside the code conformance process: if an owner wishes to upgrade the seismic design -to obtain better performance- the definition of that upgrade and the determination of benefits is strictly between the owner and engineer. While current codes do have provisions directed to obtaining superior performance for essential buildings the expectations are not explicitly defined, and the relevant code provisions consist mainly of increasing the global force level for the building and requiring certain limitations on building size and structural type.

Thus a new performance -based code which entails the selection of a performance level that is defined in the code will also need to be accompanied by a variety of educational materials directed to the design professionals and the building officials and checkers.

Architects are not concerned with the detailed methodologies of a seismic code. Codes do not generate or even control architectural design: they ensure that certain design and material issues are taken care of in a uniform manner and in this they generally *ease* the architect's design load: for example, it is not necessary for the architect to calculate the number of toilets or the width of a stair, because the code provides (minimum) standards for these and many other things.

The 1991 Uniform Building Code has 1008 pages of provisions, of which 34 are seismic; in addition the architect's design must conform to energy and accessibility standards, and to electrical and mechanical codes. The seismic chapter in the UBC is one of the shortest but also one of the most technical and so for all but the smallest project, the architect delegates this section to his structural consultant and thinks no more about it. Advent of a performance-based code, however, would require the architect to be very familiar with the definition of performance levels and the cost/benefit implications of the choice of level. As the main communicant with the client it will be critical that the architect's knowledge of these issues is accurate and well-founded, for often the determination of seismic objectives would occur well before the structural engineer is involved.

Engineers would be most affected by a large code change. Office practices would be affected and engineers at all levels would need a degree of "re-training". Some offices would embrace the new methodology with enthusiasm and rapidly train their staffs in the new methods, others would delay the effort as long as possible and have to dragged into the new world - either by building departments or clients: most offices would fall somewhere in between these two extremes, depending on their size, clientele, business state, attitude to employee training, intellectual curiosity versus production orientation and perception of the new procedures as opportunity or hindrance

A focus on performance objectives and the *prediction* of structural behavior tends to be alien to typical engineering practice, which has a strong problem solving design focus, with, currently, a strong analytical bias. The advent of computer programs into engineering practice has tended further to shift conceptual thinking from the project engineer to the software developer. This trend will need to be arrested as engineers are called upon to discuss performance concepts with architects and other clients.

While there will be a need for the education of building officials in a new code methodology, it is possible that the changes will not be as far-reaching as for the members of the design team. For code purposes, issues of performance-based design must be resolved into unambiguous language and relatively simple procedures, and a code will deal with precepts rather than concepts. Indeed, one of the issues for the technical side of performance -based design is the extent to which it can effectively be translated into code procedures, or make the transition from advisory guidelines to a legally enforceable document. It is important that experienced building officials are involved in the development of the Guidelines and Provisions from their inception to ensure that methodologies are not developed that are incapable of translation into a workable code.

These three professional groups represent the main audiences for an educational effort. For some topics - the conceptual basis and philosophy of a new code - common materials and joint workshops and seminars will be appropriate and necessary. For others, specific materials will be necessary: for engineers, in-depth seminars on analysis procedures, and case-studies will be needed. Architects will need careful briefing on owner-related issues to guide them in performance level selection. Building officials will need materials that lay out in precise detail the entire methodology and the procedure for checking against every provision.

Finally, for all groups, acceptance and understanding is more likely to occur if representatives of these groups are involved in the development from an early date, so that the effort is seen as broadly participatory rather than as a small group of experts developing a methodology in isolation.

Alternatives

1. When the new Provisions and Commentary are complete, develop a set of educational materials oriented towards the three main audiences: architects, engineers and building officials. Design and implement workshops directed towards these audiences, including workshops both for joint professional groups and single profession audiences.

2. Begin an educational program as soon as some of the main philosophical and methodological issues begin to be resolved, and the Guidelines document is produced. Seminars and workshops can be used both for education and as a means of procuring participation from key groups in the more detailed development of the Provisions and Commentary.

Recommendation

Alternative 2 is recommended. Work should begin on a preliminary education plan including publication types and workshops and seminars matched to audiences, and a time line related to probable Guideline and Provision development.

Issue 2.4: Communications among the Project Team

Issue Statement

What are the implications of a performance-based seismic code on the needs for communication between the owner and the design and construction team?

Background

The traditional model of the design and construction process envisages a fragmented group of professionals responsible for various technical aspects of the projects, coordinated (and generally hired) by the architect, who acts as the voice of the design team to the owner. The design team produces contract documents: there is a contract selection process and the selected contractor is charged with executing the design for a fixed sum in accord with the plans and specifications. The contractor in this model is out of the decision-making loop: he does not participate in design decisions but simply follows plans and specifications.
In recent years this model has been breaking down and new project delivery procedures are being followed: the rise of construction management and construction consulting brings the builder into the design decision process; cost consultants are employed from the inception of the project; the professionals as a team or "partnership" is becoming stressed, sometimes in a formal manner.

Some of the incentive for the latter move arises from the impacts of litigation: the concept of independent professionals responsible for isolated portions of the work has been attacked by law suits which invariably name the whole design and construction team (and often more). In this, perhaps, the lawyers are reflecting the reality of design and construction, that decisions *are* inter-related and the professionals do not, or should not, work in virtual isolation one from another.

These trends suggest that, rather than continuing to attempt to and draw lines around professional areas of understanding and responsibility, the complexity of modern design and construction will best be served by increased interaction among the design and construction team and with its client. Performance-based seismic design encourages, or even requires, a move in this direction because it forces discussion of fundamental project objectives at the initiation of a project that have implications for the whole team as it proceeds down its design and construction path.

The new procedure will change the roles of the project principals. The owner will have to make decisions that previously he has not been called upon to make, and understand performance alternatives that previously he did not know existed. The choice of protection level will largely be determined by the owner, and so he must understand the alternatives.

To the extent that the architect continues to be the main conduit of project information to the client he must now explain the technical basis of choices that previously he has not been called upon to provide. He may choose to delegate this (to his engineer) but often, particularly at the opening stage of a project, the architect must be prepared to brief the client. In the very early stages of a project the architect must respond to a wide variety of technical concerns from his client, and he cannot (except in large projects) expect always to have his engineer at his side to respond to questions of broad strategy and scope.

It may also be suggested that performance-based seismic design should be seen at the project level as part of a broader vision of performance improvement that other teams in the design and construction community are working on. Such issues as environmental improvement (lighting, climate and acoustical), fire safety and building accessibility are currently all the subject of research and development from theoretical, marketing and regulatory bases.

The engineer will have a pivotal role as performance-based design is implemented. Clear and accurate information and judgment must be provided to the architect, and owner if called upon to do so. Pressures for assurances that he may find difficult to provide may be applied: a performance-based design methodology must provide him with clear understanding of the limits of capability.

In particular, a difficult technical problem is created in the relationship between architectural and structural design. A performance-based code is unlikely to be able to cover all the possible configurational combinations that the architect can present the engineer, and structural performance is always influenced-sometimes strongly- by global configuration choices or localized architectural decisions relating to the size, shape and location of structural members. If performance-based design is to succeed, architects and engineers must communicate using a shared fund of knowledge that is currently largely non-existent among the general body of professionals. Communication will also need action: the willingness to seek innovative solutions or accept design changes if desired performance is to be achieved.

Alternatives

1. Wait until a new performance-based code is close to implementation and then develop programs aimed to improve communication and understanding among the design team and owner representatives.

2. Begin immediately to develop programs of joint seminars and workshops through the leading professional organizations to explore the implications of performance-based design and to participate in the development of its methodology.

3. As the basic concepts of performance-based design become established develop a program of seminars and workshops to explain these concepts and clarify terminology, etc. Use these activities to provide feed-back to the detailed development of the methodology and the Guidelines. As an example, for architects, such activities could be introduced in the new mandatory continuing education requirements now being developed by the American Institute of Architects, which are expected to be in place nationwide by 1996.

Recommendation

Alternatives 2 and 3 are recommended. Explorations should be conducted with the main professional institutes and associations with a view to joint informational programs. A preliminary plan of information exchange, including publications, workshops and seminars should be developed.

Issue 2.5: Liability Issues

Issue Statement

What liability issues might arise if a performance-based seismic code is implemented?

Background

The possible liability problems to be encountered in the use of a set of seismic provisions that provided for flexible standards and varied impact was considered in the publication *Seismic Rehabilitation of Buildings - Phase I: Issues Identification and Resolution (FEMA Publication 237)*. In the discussion on legal and political issues (Issue 5), the concern was for the legal implications of standards that differ for new and existing buildings, and that might have different cost or benefit effects on different buildings. The legal opinions presented in this discussion provide some useful guidance for looking at the more specific issue of provisions that provide criteria for varying levels of performance, and hence imply that specific seismic performance can, to some extent, be assured.

The background discussion of Issue 5 noted that ..."legal opinions presented here tend to confirm commonsense engineering views as to reasonable limits on the costliness of retroactive measures, and as to the possible latitude in allowing alternative procedures and strengthening levels."

..."trade-offs should be acknowledged between cost of upgrading and the benefit of increased safety or improved performance. Where possible, options should be provided.."

"The Guidelines must explain their purpose, such as by defining specific performance goals and providing commentary on the difference between life safety and property protection." (FEMA 237 p.47).

These opinions, while not directly addressing the issue of varied performance levels, open the door to a rational approach to the problem.

Recent discussion with the author of these opinions* has confirmed the continued relevance of the opinions in the FEMA 237 Publication. However, an approach to a performance-based code, with alternative levels of performance, would in the author's opinion be "close to the cutting edge of the law". He was not immediately able to quote precedents for the situation, and felt that some legal research would be advisable, and very interesting, as the development of the Guidelines proceeded. He did, however stress, that the issue of whether the various performance levels would aim to provide varying levels of *safety,* and be expressed as such, would be important in any litigation.

This suggests very strongly, as an initial "common-sense" approach, that a clearly expressed "life-safety" intent be defined as one performance level, and other levels would be above this and primarily related to continued function and/or reduction of property losses.

Parenthetically, in looking for precedents of regulation that provide for varying levels of safety, one might consider the automobile airbag situation. In automobile safety there is public acceptance of the fact that absolute safety cannot be guaranteed. Also, the present situation indicates that the public will accept a situation in which a certain (not clearly defined) basic safety level is provided for but significant improvement over this level can be obtained by voluntary purchase (of airbags). Currently, one can buy a new car without airbags, but considerable advertising expense is devoted to encouraging consumers to install them. (One should also note that this encouragement is provided not in the form of statistics or cost/benefit analyses but by the use of emotive TV images of happy children and shattering test dummies). This experience suggests that perhaps the public is willing to do its own cost/benefit analyses of alternative safety levels, but does not really want very explicit statements of engineering performance. The latter point is more accurately characterized as the advertising agencies assessment of public desire.

The entire set of alternatives proposed in FEMA 237 for the Legal Issues is reiterated here, because they represent relevant legal opinion on a set of issues very close to those implicit in a performance-based code.

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* Crane Miller, Attorney, Office of the general Counsel, FEMA, Washington ,DC

Similarly, the recommendations proposed for the liability issue in FEMA 237 (Issue 5.2 Liability) might serve as useful guidance in the approach to a performance-based seismic design approach. The second recommendation (alternative 4) comes very close to covering the main issues of concern for a performance-based code.

Alternatives

1. Assume that liability is such a major constraint on the writing of the Guidelines that only provisions that can be backed up by completely verifiable facts should be included.

2. Assume that liability concerns can be eliminated as long as the right disclaimer language is provided at the beginning of the Guidelines, so that whoever uses them will be protected.

3. Assume that liability concerns cannot be eliminated but that they are not a major barrier or concern in the writing of the Guidelines.

4. The Guidelines should clearly state and define their purpose and intent (e.g., life safety) to the extent possible. They should include some narrative on their limitations (for instance, if the Guidelines are not designed to ensure the ability of a building to function after an earthquake). The Guidelines should also contain a disclaimer of any guarantee that adherence to the Guidelines will necessarily accomplish their purpose and intent.

Recommendations

Alternatives 3 and 4 are recommended. Legal studies should be initiated (perhaps through the FEMA office of General Counsel) as to the implications of performance-based design, and legal precedents. A report should be prepared and form the subject of a workshop primarily addressed to architectural and engineering practitioners, building officials and construction oriented legal professionals and insurance companies.

ISSUE PAPER #3

Risk Assessment and Structural Reliability

by

Anne Kiremidjian

3. Risk Assessment and Structural Reliability

3.1 Introduction

Probability-based codes were first introduced in the late 1960s and currently form the basis for most building codes in the United States. Some of the advantages of a probability-based code include (a) the consideration of uncertainties in loads and resistances; (b) the development of design requirements that are consistent with an acceptable risk criteria; and (c) similar safety requirements for similar design of different materials or for different designs of the same material. While probability-based codes have become the standard for design of buildings and other structures in the United States, seismic codes include probability information only at the ground motion level and then only in the form of seismic hazard maps. Seismic hazard maps provide summary information of the potential ground shaking over a large region and as such they provide initial load information for the design of most conventional structures. However, site-specific ground motions are necessary for the design of the majority of high-rise structures. Furthermore, ground motion time histories are needed for important or critical structures. While seismic hazard maps are developed using probabilistic models, site-specific response spectra and time histories are most often obtained for the "maximum credible" or heuristically-defined "maximum probable event."

Current seismic design requires that structures sustain minimal amount of damage and maintain their functionality following a moderate earthquake and that they do not collapse in the event of a major earthquake. These criteria have shown to be inadequate following recent earthquake events in California. While the majority of structures performed extremely well during the Loma Prieta earthquake of 1989, many others remained unserviceable for a prolonged period of time following this earthquake. This problem has led to the reevaluation of the criteria used to develop seismic codes. This reevaluation provides the opportunity to formulate these codes with current advances in probability and reliability analysis. This process will bring seismic codes in line with other design codes in the United States and will facilitate future improvements.

The main components in probability-based codes include: (I) identification of performance limits states, (ii) calibration of the safety limits for these performance criteria based on existing design, (iii) definition of new acceptable safety limits, (iv) development of demonstration designs, and (v) development of appropriate supporting documentation. Prior to the implementation of this procedure, however, several issues need to be resolved. Table 3-1 identifies the main issues related to the development and implementation of probability-based performance criteria seismic codes.

Table 3-1: Summary of Issues in Risk Assessment and Structural Reliability

3.1 Identification and Quantification of Risk: Should different performance criteria be defined based on acceptable risk levels?

3.2 Estimation of Safety: What approach should be used to define risk-based performance criteria?

3.3 Probability-based Performance Codes Using Reliability Formulations: Should component or system reliability methods be used for defining risk levels and developing design parameters?

3.4 Uniform Hazard or Uniform Risk Seismic Maps: What structural modeling parameter values should be used?

3.5 Aggregated Versus Individual Risk: Should the code be prescriptive or descriptive? (i.e., should design parameters be quantified, or should acceptable risk or safety levels be defined and procedures for attaining these levels be provided in the code?)

3.6 Verification of New Code: What approach should be used to verify the proposed performance-based design code?

3.7 Treatment of New Materials: How should new materials be treated?

Issue 3.1: Identification and Quantification of Risk

Issue Statement

Should different performance criteria be defined based on acceptable risk levels?

Background

Seismic design is currently based on two criteria: (i) provide life safety in the event of a great earthquake and (ii) provide a serviceable structure after a moderate earthquake. With this criteria the hazard posed by future earthquakes is assessed and represented primarily through hazard maps or through site-specific hazard analysis. The design specifications are not based on the likelihood or probability of reaching a particular limit state of the structure but are developed on the basis of limits that have been defined heuristically and/or analytically. For example, current ATC, NEHRP, or SEAOC seismic design requirements list strength reduction factors R_W for different types of structures. These factors were not developed on an analytical basis to reflect the likelihood of damage or collapse of a structure when subjected to different levels of ground motion. Instead, they were developed on heuristic arguments drawing on past experience and observations of the performance of different structural types.

As a result of this approach, the risk of damage, loss, down time, and long-term consequences are not known with existing structures designed under these code requirements. Furthermore, owners are not given the opportunity to select different design levels depending on the risk or potential consequences of these design levels. A code should provide minimum requirements, however, it should make provisions for rational decision making on the part of the owners. Engineers should be well versed in that respect to provide the appropriate information for such rational decision making on the part of the owner.

Alternatives

1. Develop a set of performance criteria for redefined safety indices. The safety indices can be uniform for all structural types or may be varied according to structural systems.

2. Develop a set of performance criteria with corresponding probabilities of occurrence and consequences. Provide the tools for assessing the risk associated with each performance level.

3. Develop a set of risk levels in terms of the probabilities of losses (i.e., monetary loss, down time) and identify the performance levels based on these acceptable risk levels.

4. Develop a minimum cost/maximum safety approach algorithm for the selection of the optimal performance criteria.

Recommendation

Alternative 3 is recommended.

Issue 3.2: Estimation of Safety

Issues Statement

What approach should be used to define risk-based performance criteria?

Background

Structural performance criteria can be defined in terms of specific quantitative limits that the structure can attain under various loads or can be postulated in more general terms where the performance is described qualitatively. For example, quantitative performance limits may include maximum deformation, maximum interstory drift, maximum allowable yield stress of critical member, etc. Current seismic design criteria as defined in the introduction are more qualitative than quantitative stating desirable overall performance of structures. Risk-based criteria requires that performance criteria be defined in quantitative terms and corresponding risks be evaluated. Risk is defined as the probability of failure of the structure to meet a specified performance criteria times the consequences of that failure. Thus if the consequences are measured in terms of monetary loss, then the risk will be the expected dollar loss. In order to evaluate the expected dollar loss, it is necessary to determine the probability that the structure will fail to meet its performance criteria and the corresponding dollar losses when subjected to various levels of ground shaking resulting from different magnitude earthquake events. Such analysis can be performed on an annual basis or for the life of the structure.

Current load resistance design factor codes do not evaluate directly the probability that a structure will not meet its performance criteria nor do they consider the potential losses from failed criteria. Instead, load and resistance factors are developed on the basis of preassigned safety indices. These indices are evaluated by calibrating the safety levels of existing structures whose performance is deemed to be satisfactory. Seismic codes, such as the 1992 NEHRP or the 1992 SEAOC Seismic Design Recommendations do not evaluate the overall safety.

Alternatives

1. Define a set of threshold probabilities and determine corresponding performance levels using reliability analysis methods.

2. Define risk in terms of expected loss and define a set of acceptable loss threshold levels. Determine corresponding performance levels based on the acceptable risk values.

3. Define a set of quantitative structural performance criteria and prescribe methods for evaluating the risk from exceeding these criteria.

Recommendation

Alternative 2. is recommended with Alternative 1. as a fall-back position.

Issue 3.3: Probability-Based Performance Codes Using Reliability Formulations

Issue Statement

Should component or system reliability methods be used for defining risk levels and developing design parameters?

Background

Regardless of the alternative selected under Issue 3.1, reliability analysis methods will need to be utilized. Current design codes are based on a safety checking format for assessment of load resistance factors. For that purpose, first-order reliability analysis methods applied at the structural component level were implemented. For example, the load resistance factor design for steel or concrete structures was formulated using this approach. Load factors and load combinations developed for the most recent ANSI Standard A58.1 are obtained based on first-order component reliability analysis methods. Using the same methods, resistance factors were developed consistent with the uncertainties in the material properties for each material.

Recent advances in structural system reliability and reliability-based optimization methods have brought the state-of-the-art a step closer to a systems approach to structural code development. Numerous difficulties, however, still exist with the systems approach in structural reliability. For example, systems safety indices have not been defined. Time varying systems reliability is not yet sufficiently developed to be implemented to earthquake safety evaluation of structures. Many computational difficulties with systems reliability analysis methods have not been resolved. A systems approach for a performance-based seismic code, however, should not be discounted. Instead, it should be fully investigated and its long-term implementation formulated at this stage.

Alternatives

1. Implement component-based safety checking format for each performance criteria.

2. Develop limit states that capture the essence of system-based performance criteria, and apply component reliability analysis methods for assessment of (i) safety (risk) levels, and (ii) design parameters at specified safety levels.

3. Develop simplified systems reliability analysis methods for assessing the risk level for each specified performance criteria and prescribe procedures to evaluate design parameters for selected performance criteria.

4. Use time-dependent component reliability analysis formulations.

5. Develop time-dependent systems reliability analysis formulations.

Recommendation

Alternative 3 is recommended with Alternative 2 as a fall-back position.

Issue 3.4: Uniform Hazard or Uniform Risk Seismic Maps

Issue Statement

Should design ground motions be based on uniform exposure hazard or uniform risk?

Background

The potential for ground shaking throughout the United States is represented by seismic hazard exposure maps. Such maps typically show contours of effective peak ground acceleration, velocity or spectral acceleration and velocity at specified structural periods. Seismic hazard maps developed over the past fifteen years have used simple Poisson models to estimate probability of seismic events. Contours are typically developed for specified return period of event or for equivalent probability of exceedence of the ground motion level over a specified period of design life. For example, the maps given in the current NEHRP Seismic Design Recommendations are for 500 and 2500 years return period of events; or respectively, for 10 percent of exceedence in 50 years or 10 percent of exceedence in 250 years. These maps prescribe ground shaking for a constant or uniform hazard level throughout the United States. The risk of economic loss, life loss, injury, and long-term economic consequences are likely to vary greatly between the western United States and the central and eastern United States. At the same exposure hazard, the likelihood for damage and loss are considerably greater in the eastern United States than in the western part of the country because of differences in seismic design practice. For the same hazard level, ground shaking exposure is likely to be considerably lower in the eastern U.S. because of the lower seismicity levels in that region. However, the overall risk may be comparable or even greater at these levels because seismic design requirements are either nonexistent or have been imposed only recently. As a result, there is a greater inventory of hazardous buildings.

Alternatives

1. Develop seismic ground exposure maps based on uniform hazard level nationwide.

2. Define different hazard levels for different parts of the United States.

3. Define uniform acceptable risk levels and develop uniform risk exposure maps.

Recommendation

Alternative 3 is recommended.

Issue 3.5: Aggregated Versus Individual Risk

Issue Statement

Should the code be prescriptive or descriptive? (i.e., should design parameters be quantified, or should acceptable risk or safety levels be defined and procedures for attaining these levels be provided in the code?

Background

The approach considered in the load resistance factor designs to develop uniform load factors and resistance factors for different materials. Then design procedures are specified with minimum requirements explicitly stated in the code. Seismic design requirements, such as these given in the ATC-3, SEAOC, and NEHRP are prescriptive providing tables and procedures for minimum design requirements. If a risk-based performance criteria is to be developed, then some latitude should be given to the designer to satisfy the risk level specified by the client. In such instances, a description or a guide will be needed to guide the designer leading to an acceptable design level consistent with the specified risk. It is important in such an approach to also include certain minimum requirements as a safeguard against excessively low design levels.

Alternatives

1. Develop prescribed load levels such as these given in a uniform seismic risk map and corresponding resistance parameters for design of different materials.

2. Develop a set of acceptable risk levels and develop design guidelines leading to these acceptable risk levels.

3. Develop a combination of Alternatives 1 and 2.

Recommendation

Alternative 3 is recommended.

Issue 3.6: Verification of New Code

Issue Statement

What approach should be used to verify the proposed performance-based design code?

Background

New design codes are most frequently developed with the objective to improve design procedures of previous codes and to incorporate current knowledge. When such codes are to be verified, however, the verification is typically performed by comparison to existing designs. In verifying new design codes, there ought to be at least two objectives: (i) to verify that the new code provides at least as much safety as earlier codes, and (ii) to verify that the improvements in design postulated at the onset of the new code formulation are fulfilled. The second objective is often difficult to achieve by conventional means.

Reliability formulations provide the rational for evaluating the safety of a structure that are particularly suitable for comparison purposes. Thus, if the safety level (or probability of failure or damage) of two structures identical in plan, elevation, and general configuration but each designed to different code specifications are evaluated, then this measure can serve as the means of comparison and verification that they satisfy minimum safety standards.

The difficulties, however, arise due to the still poorly understood behavior of structures under random dynamic loads such as those imposed by earthquakes. Thus, although the behavior of many structures is somewhat predictable, there is always some element of "surprise" following each major earthquake. It is this element of surprise that makes it difficult to fully and adequately verify new design specifications.

Alternatives

1. Prescribe a set of acceptable safety levels based on current design that has been subjected to significant earthquakes. Evaluate the safety levels of a series of designs developed under the new proposed code. The test designs should consider different configurations and design conditions.

2. Perform laboratory tests for model structures designed under the proposed design.

3. Develop an analytical experiment where site conditions are specified and request that different engineers provide designs based on the proposed design code. Develop a design based on the earlier design code. Then compare the designs based on safety evaluation and/or based on a panel of experts. Perform an independent safety evaluation of each design using reliability analysis techniques.

Recommendation

A combination of Alternatives 1 and 3 are recommended.

Issue 3.7: Treatment of New Materials

Issue Statement

How should new materials be treated?

Background

With the emergence of new materials that can be used for construction, the issues of how to provide design guidelines and how to test the performance of such designs need to be resolved. Laboratory experimentation can provide basic material specifications such as elasticity or plasticity limits, deformation limits, durability, etc. However, the difficulty arises when the actual performance of the material is questioned when it is an integral part of a structural component or may represent an entire panel or even an entire structure. Reliability analysis techniques can provide the means for comparisons of safety levels for defined limit states. In order to evaluate the reliability of structures with new materials, however, it is necessary to have information on the limit states of the structure which require that the behavior of the structure be well understood in addition to knowledge of the material parameter uncertainties. Shake table experiments can provide insight on the behavior and possible limit states for such structures.

Alternatives

1. Perform laboratory tests to assess material parameters and the uncertainties associated with each parameter. Hypothesize different limit states for the structure and evaluate the probability reaching these limit states.

2. Perform shake table tests subjecting the model to an ensemble of past earthquakes and observe the behavior of the structure with these materials. Identify critical limit states based on these experiments and evaluate the reliability of hypothetical designs under these limit states.

3. Use a combination of Alternatives 1 and 2.

Recommendation

Alternative 3 is recommended.

ISSUE PAPER #4

Issues Related to Structural Analysis and Design

by

Steve Mahin and Bill Holmes

4. Issues Related to Structural Analysis and Design

4.1 Introduction

A major drawback of seismic design procedures incorporated in current building codes is that they are indirect in their approach to achieving performance goals. Structures are analyzed for subjectively modified ground motions using simplified dynamic analysis methods that do not account for expected nonlinear behavior, are evaluated considering estimates of response parameters often unrelated to those anticipated during actual earthquakes, and are detailed using prescriptive procedures seldom based on realistic calculations of seismic demands. Such codes are based on design experience, post-earthquake damage investigations, and limited amounts of theory and research. As such, they are generally able to achieve structural designs providing adequate protection of life safety. However, there is increasing feeling that modern structures are often designed more conservatively than required for life safety, yet little indication can be gleaned from the codes of the actual performance anticipated or of how even higher levels of performance can be achieved. On the other hand, there is increasing concern that code provisions may provide only marginal safety for some types of structures and for certain seismic environments. This situation is further exacerbated if one considers the evaluation and retrofit of existing structures. Thus, a key challenge and motivation for performance-based design methods is to devise a consistent, realistic, yet practicable framework within which the designer can ensure that a new or existing building will likely respond under the design earthquake in conformance with explicitly stated performance goals.

One approach to performance-based design to is to simply stipulate additional prescriptive measures to cover special circumstances, new types of structures and unusual seismic environments. While this may have a desirable short term benefit, this strategy is likely to introduce further complexities and inconsistencies into the overall design process. Moreover, it provides no guidance on how to achieve performance goals beyond life safety, evaluate and retrofit existing structures, and treat structures with unusual configurations or site conditions and employing new materials or structural elements. A more fundamental approach is needed to provide a solid foundation for a comprehensive performance-based code.

Many say that performance-based design methods revolve around analytical procedures capable of reliably predicting seismic response. In the simplest sense, a designer needs simply to compute the response of a structure to the design earthquake and to compare computed responses with specified performance criteria. This requires advanced, yet user friendly, computer tools as well as validated modeling procedures. Significant advances in computer technology and analysis software make this approach theoretically possible. Yet, wide variations have been noted between responses predicted using different programs and modeling assumptions. Importantly, this simple deterministic approach does not account for the uncertainty in input motions and structural modeling parameters. Similarly, it is not certain what level of sophistication in modeling is necessary to realize the desired level of accuracy. Considerable basic research and directed studies are required to develop this analytical technology to the point that it is suitable for production applications.

Not withstanding the above comments, one would not want to always employ the most complex and detailed analysis procedures for all structures, especially small conventional buildings. Directed analytical investigations should be used to identify appropriate design and analysis procedures for different classes of building systems, performance categories and seismic environments. In this regard, it is desirable to develop new approaches to design (e.g., based on displacement or energy) which will result in a structure in keeping with its performance goal.

To achieve structures capable of performing in conformance with stated performance objectives, it is necessary to understand which characteristics of ground motions might adversely influence structural response, especially response in the inelastic range. For instance, numerous studies have indicated that motions likely to be experienced at soft soil or near-fault sites or those with particularly long duration may have adverse effects on the response of some structures. These studies are, however, far from conclusive and have not been carried out to the point where they can provide definitive design guidance.

A corollary issue relates to the influence on performance of the structure's configuration, material and load resisting system, the foundation and nonstructural components. Studies on what structural forms lead to structures inherently suitable for various performance objectives will help engineers select desirable seismic resisting systems, modify ones that analysis indicates perform in an unsatisfactory manner and improve understanding of seismic response. Such studies can be effectively used to identify and validate simplified design procedures for certain classes of structures and performance categories.

The use of a performance-based design approach implies the need for higher levels of confidence in the ability of the structure to perform as intended. Thus, it is desirable to benchmark analytical methods and structural models through integrated experimental and analytical studies, and validate their adequacy for design purposes through detailed case studies and post-earthquake investigations.

It is clear that performance-based design procedures will generally require greater appreciation on the part of the designer of structural response and of the various structural, ground motion and dynamics factors that influence this response. The development of technical and educational materials and mechanisms is a fundamental aspect of developing performance-based design and analysis procedures.

These general concerns regarding analysis and design are examined in more detail below. Twelve inter-related issues are identified. Issue 4.1 and 4.2 focus on development of computer tools, while Issues 4.3 through 4.6 relate to practical details of modeling and analysis of building systems. Issues 4.7 and 4.8 attempt to identify and quantify those earthquake and structural factors that influence seismic performance. Information developed in the activities recommended in Issues 4.1 through 4.8 is used in Issues 4.9 through 4.11 to identify, develop and verify basic and simplified performance-based design procedures. Issue 4.12 addresses knowledge dissemination and professional training as they relate to the analysis and design. These issues are summarized in Table 4.1.

Table 4-1: Summary of Issues Related to Structural Design and Analysis

4.1 Development of Analysis Tool-Box for Earthquake-Resistant Design: What types of structural analysis procedures are required?

4.2 Development of a Design Tool-Box: How can computer tools help in design?

4.3 Development of Appropriate Building System Idealizations: How should buildings be modeled?

4.4 Development of Guidelines for Suitable Modeling Parameters: What structural modeling parameter values should be used?

4.5 Identification of Engineering Performance Parameters: What are the important engineering parameters to be monitored/evaluated?

4.6 Issues Related to Uncertainty: How should one assess the relation between demand and capacity for these performance parameters?

4.7 Characterization of Ground Motions: What characteristics of ground motions should be considered in specifying design earthquakes?

4.8 Influence of Building System on Performance: What features of a building system tend to make it inherently safe or vulnerable to seismic effects?

4.9 Selection of Basic Analysis/Design Methods for Performance-Based Approaches: What are reliable methods for designing structures that satisfy performance objectives?

4.10 Identification of Simplified Performance-Based Design Procedures: Can simplified performance-based design methods be developed for certain classes of buildings and seismic environments?

4.11 Verification Studies: Can performance-based design methods achieve their objective in a practical and reliable manner?

4.12 Educational and Training Issues: How can the profession be aided in implementing performance-based design methods?

Issue 4.1: Development of an Analysis Tool-Box for Earthquake-Resistant Design

Issue Statement

What types of structural analysis tools are required for performance-based design?

Background

Simply speaking, one would desire to be able to analyze a structure accurately to determine its response to a specified motion. Thus, with a rationally defined input motion and a set of specific performance criteria the designer should be able to evaluate the adequacy of a design.

Alternatives

1. Elastic methods of analysis should be utilized. Market pressures and advancing computer technology will likely produce the computer tools needed to carry out such elastic analyses within a relatively short time. Additional efforts are needed to facilitate modeling of features such as soil-foundation-structure interaction, interaction of nonstructural and structural components, joint and diaphragm deformations, and so on. Additional commercial effort is needed to facilitate interpretation and visualization of results and to link structural analysis modeling information with computer-aided design and drafting programs.

2. Computer tools need to be refined, extended and verified to assess the cyclic inelastic behavior of common structural sections, members and connections. Such analyses are already possible for certain types of members (e.g., plastic hinge response in steel and reinforced concrete flexural members), but the sensitivity of computed behavior to local detailing and material variations and the impact of undesirable behavior modes (e.g., local bucking of rebar or flanges) has not yet been adequately treated. Consensus has not yet been reached on modeling many types of common members and elements (e.g., concrete or plywood shear walls). Additional concerns on this general topic are discussed in Issue Paper 6: Structural Components. Development and verification of design oriented, computer tools to assess local behavior of members and elements are viewed as a high priority, moderate term effort requiring moderate amounts of funding for basic research as well as for directed studies.

3. Computer tools are needed to predict the inelastic dynamic response of complex three-dimensional structures. Extensive efforts are believed to be necessary to develop: a versatile and robust, yet efficient numerical workhorse to simulate seismic response of large, highly nonlinear systems; geometric modeling capabilities for idealizing three-dimensional buildings with flexible diaphragms, compliant foundations, geometric nonlinearities and other commonly encountered features; and a user-friendly interface environment to facilitate input, execution, and response interpretation and visualization. It is essential that these tools be design, rather than research, oriented. This is viewed as a high priority, moderate term effort. Because of the multitude of technical problems anticipated in implementing such programs and the need to incorporate state of the art numerical and modeling techniques, this effort is viewed as involving basic research and problem focused studies to supplement market-driven development efforts.

Recommendations.

Primary emphasis should be placed on Alternative 3. It is expected that more than one program should be developed, and specialized user interfaces may be required. To maximize the usefulness of such programs and interfaces, and the ability to incorporate new numerical models of members and elements, uniform standards for these programs should be established. Alternate 2 is viewed as a necessary prerequisite to accomplishing a performance-based design method. It is expected that elastic analysis methods covered in Alternate 1 will continue to be needed (e.g., for serviceability limit states and structures requiring essentially elastic response), but relatively little research and development work is needed to make these tools available to the designer.

Issue 4.2: Development of a Design Tool-Box for Earthquake-Resistant Design

Issue Statement

How can computer tools help the designer achieve structures satisfying performance objectives?

Background

While computer simulation programs can identify potential seismic weaknesses of a building , they cannot by themselves indicate to the designer those design changes that will improve response. A knowledgeable engineer can often identify these changes on the basis of experience. However, even these designers may have difficulty in interpreting the response of complex or unusual structural systems. Recent advances in computer technology and design theory make software possible to assist the engineer in selecting structural systems for particular applications, in interpreting results of structural analyses and identifying design improvements.

Alternatives

1. The best means of interpreting results and selecting structural systems is by the designer working with other design professionals. Computer programs will interfere with and obscure this process, and should therefore be avoided.

2. Efforts are needed to develop special purpose computer programs based on optimization, system reliability and other concepts to achieve structures capable of attaining their performance goals. Advanced technology from computer science and operations research may be able to help the designer interpret analytical results and converge on a design most conforming to the performance criteria. Issues related to uncertainties in the characteristics of the building and input motion properties and to vagueness of the target performance criteria can be taken into account with such procedures. This is viewed a long term effort involving basic research initially and directed studies when practicable methods are identified.
3. Efforts are needed to utilize capabilities of knowledge-based and expert systems to aid designers in a wide range of activities, from selection of appropriate structural systems to optimal detailing of structures. Recent innovations in knowledge-based systems from advanced manufacturing process integration may be applicable to seismic design. Such methods hold the opportunity for assisting in technology dissemination and implementation as well as for producing more economical designs which will mitigate increased costs associated

with providing enhanced seismic engineering and resistance. This is viewed a as long term effort involving basic research and directed studies.

Recommendations.

While the engineer must remain in control of the design process, it is believed that a wide range of practical computer tools can be developed to aid the engineer in assessing results of structural analysis and in selecting improved and more cost effective designs. The efforts described in Alternatives 2 and 3 are viewed as desirable and in a sense fundamental to long term implementation of performance-based design methods. Knowledge-based information retrieval systems associated with Alternative 3 may have a significant role in technology dissemination and implementation (see also Issue 4.12). Research and directed studies are needed to develop and assess these design tools.

Issue 4.3: Development of Appropriate Building System Idealizations

Issue Statement

How should buildings be modeled for performance-based design?

Background

Computer idealizations need to be provided with the capability of realistically representing the behavior of common structural and nonstructural members and elements. For elastic response, models for beams and columns are well established, but modeling of shear walls, diaphragms, joints, floor systems and foundations require improvement and verification. Extensive studies are needed to complete development of realistic idealizations of the inelastic response of members and elements. For example, even for beams, the simplest of structural members, few models have been developed to account for the composite action of the beams and attached slabs, the spreading of plastic hinges due to transverse (gravity) loading and material strain hardening, shearing and axial deformations in plastic hinge regions, cyclic deterioration and endurance, and so on. While these issues may not be important for all structures, definitive guidelines for the applicability and accuracy of modeling procedures are currently absent.

Many current inelastic models only mimic the general phenomenological behavior of the elements they represent. In fact, *good* behavior is typically assumed and it is left to the designer to provide details to ensure this behavior. Such models provide little guidance on the adequacy of local details or on the response of structures with members having small or moderate ductility (e.g., as may be found in existing structures, in new structures to be located in areas of low seismic risk, and so on). Additional effort is thus needed to model and assess realistically behavior, especially that associated with the limit states introduced by performance-based design methods. For instance, member models should be able to detect and account for initiation of yielding, the onset of rebar (or flange) buckling, spalling of concrete and other local features that may influence performance assessment.

Computer programs should also be provided with the capability to simulate realistically the interaction of the structure with attached nonstructural components, with its supporting soil and foundation, and with adjacent structures. All of these phenomenon have been seen to have a profound effect on building performance.

Alternatives

1. Continue to allow designers to select modeling based on available information and simplified computer representations.

2. Little of the information available on member and component modeling has been compiled, synthesized, and evaluated in a form usable by the designer/analyst. The adequacy of current models needs to be assessed. This assessment should include the inelastic as well as elastic ranges of behavior for: (a) structural elements, (b) nonstructural components, including cladding and framing members not normally intended to act as part of the earthquake resisting system, (c) supporting soil and foundations and (d) impact with adjacent structures. Particular emphasis should be placed on the ability of the analytical idealizations to detect cyclic deterioration, local failure and other limit state conditions associated with performance-based design. Needed development work and areas requiring coordinated experimental and analytical verification should be identified. Issues related to the computational effectiveness, robustness and practicability of alternative analytical models should be considered in the evaluation. This activity is an important short term topic for a directed study. It would logically precede important longer term research and directed development efforts to improve and extend modeling capabilities, to conduct sensitivity studies and to develop guidelines for use of analysis in practice.

3. Improved representations of elastic and inelastic member and element behavior are necessary. A wide variety of structural members and materials need to be considered, and issues related to foundations, nonstructural components and adjacent structures need to be included. It is essential that these representations be fully verified with experimental results. To fully utilize such analytical models, standard interface formats should be developed so that they may be used in a wide variety of structural analysis programs. This is viewed as a high priority, long term effort requiring interaction of experimental and analytical investigators in basic research and directed studies.

4. The designer /analyst may not have the background to assess the suitability of analytical models. As such, prescriptive bounds and other guidelines on the required types of models should be developed. Alternatively, for complex analyses it may be suitable to have analysis models subjected to third party review. Development of prescriptive code-type provisions is viewed as a long term process requiring the assessment of results from various research projects and studies.

Recommendations

A systematic approach to improve modeling of structures is needed and Alternatives 2 and 3 are recommended. These recommendations are very important to the realization of performance-based design methods. Prescriptive modeling guidelines may be useful, but their development needs to await development of member representations and associated benchmark comparisons of experimental and analytical results.

Issue 4.4: Development of Guidelines for Suitable Modeling Parameters

Issue Statement

What structural modeling parameters should be used for analysis in performance-based design?

Background

A computer program is only as good as its input. The old computer adage "Garbage in, garbage out" is particularly applicable to performance-based design applications. Accurate representation is needed for structural characteristics such as stiffness, mass and damping for elastic structures, and these plus strength and post-yield hysteretic behavior for structures responding in the inelastic range. A recent study funded by the Nuclear Regulatory Commission found that viscous damping varied tremendously depending on structural materials, imposed stress level, complexity of the structural system, supporting soil conditions, type and amount of non-structural elements, and other factors not normally considered in current designs. Realistic prediction of the basic mechanical properties, such as the flexural stiffness of a simple reinforced concrete beam, is difficult when considering features such as concrete cracking, composite action of beam and slab, connection flexibility and so on. Such uncertainties are subjectively *calibrated* into current code approaches. It is not clear, however, how sensitive performance estimation is to these uncertainties, or what values should ideally be used in performance-based analyses. Upper bound estimates of certain modeling parameters may conservatively overestimate some performance parameters, but provide unconservative estimates of others. To avoid at least initially hidden linkages between various aspects of design and analysis (modifying the basic shape of a response spectrum to account for uncertainties in damping, for instance), it appears that a performance based code should employ the most realistic estimate of modeling parameters possible. Upper and lower bounds may be necessary in some instances to assess the sensitivity of response to modeling uncertainties.

Alternatives

1. Modeling should be left to the designer/analyst who is most familiar with the building.

2. Information should be compiled and evaluated on available modeling parameters ranging from damping to the stiffness and strength of various building elements and materials. Modeling guidelines should be identified where information is sufficient and where the implication of the

recommendations is clear. Areas where additional research and study are needed, especially those necessitating experimental work, should be identified. The compilation and assessment of available data is a moderate short term task.

3. Analytical and experimental efforts should be carried out to fill gaps identified in Alternate 2 and to help understand reasons for observed variations in modeling parameters. Sensitivity studies to assess the effects of modeling uncertainties on performance evaluation, to develop modeling guidelines, including applicable simplifications, and to assess implications of any design recommendations should also be performed. This is viewed as an important longer term efforts involving basic research and directed studies.

Recommendation

Available data should be gathered to assist the designer (Alternative 2). Prescriptive guidelines should await the results of sensitivity studies and comparisons of experimental and analytical results such as those contained in Alternative 3.

Issue 4.5: Identification of Engineering Performance Parameters

Issue Statement

What are the important engineering parameters to be monitored/evaluated for each performance category and structural type?

Background

The results of computer analyses need to be interpreted in terms of stated performance goals. These goals may be originally expressed in conceptual terms, e.g., easily repairable damage is preferred. These qualitative goals must be translated into quantitative engineering indices that can be evaluated analytically, incorporated in computer programs and used in design. Global response quantities of interest include parameters such as displacements, interstory drifts, and accelerations. Local response quantities may include information on flexural plastic hinges (maximum and cumulative rotations, energy dissipation demand, onset of spalling, buckling or other local damage modes), joints, connections, braces, nonstructural components, and so on. More sophisticated indices based on the summation (average) or differences (changes in damage distribution) of parameters may be useful to simplify evaluation or detect certain undesirable behavior modes (e.g., weak stories). In addition to considering the mean value and dispersion of maximum and cumulative response parameters, residual deformations and forces present in the system following an earthquake may be important considerations for certain performance categories.

In addition, to evaluating response demands, available information needs to be reviewed to assess means of evaluating acceptable limits (or capacities) of these parameters for different performance categories (see also Issue Paper 6: Structural Components).

Alternatives

1. Response parameters should be related indirectly to quantities that can be predicted using elastic analyses. Expert judgment and parameter sensitivity analyses of structures of various types and materials should be used to establish limits on a few basic response parameters, such as drift and elastically computed demand to capacity ratios, that can be used to assess acceptability of overall performance.

2. A compilation, synthesis and evaluation of various parameters suggested to evaluate performance should be undertaken. This is likely a short term directed study relying heavily on existing material. Issues related to various performance categories and limit states for various materials and elements should be identified. New information based on damage/fracture mechanics, energy design concepts and so on should be considered as appropriate. Also, due attention should be placed on assessment of damage to nonstructural components. The goal of this effort is to develop definitions and gain consensus on the important engineering performance parameters for performance-based design.

3. Performance evaluation parameters should be based on realistic predictions of global and local responses. As such, analysis response representations should incorporate appropriate engineering performance parameters as output quantities. The ability of computer structural and member idealizations to characterize these parameters should be evaluated in the development and assessment of member, joint and component representations.

Recommendations

It is believed that a performance-based design method should make use of realistic estimates of seismic response. As such, Alternative 3 is recommended. Alternative 2 is a necessary prerequisite. It is believed that Alternative 1 would in the short term exacerbate the difficulty of designers visualizing actual performance. However, with continued research and directed studies, it may be possible to devise such relations between elastic response and performance goals for certain performance categories and types of structures.

Additional effort is needed to establish the specific values that can be accepted for each performance parameter for various performance categories. This effort is treated separately under issues related to structural components and nonstructural elements.

Issue 4.6: Issues Related to Uncertainty

Issue Statement

How should one assess the relation between demand and capacity?

Background

Most of analytical procedures used in structural design are deterministic. To achieve an adequate margin of safety in the face of the inherent uncertainty in seismic resistant design amplified loads and reduced capacity estimates are generally used. Issue Paper 2 describes problems related to structural reliability and risk analysis. Several specific practical difficulties arise in applying such concepts to structural analysis and design. For instance, how many earthquake time histories should be used in analysis, how is the capacity estimated (mean or a lower bound), how are modeling parameters selected, etc.?

Alternatives

1. Existing load and resistance factors should be modified based on expert opinion and available data to obtain the target performance level with the desired reliability. This is a short term, directed study.

2. Insufficient information is not now available to determine the capacity and resistance factors or other techniques that can be used to achieve the desired level of seismic reliability for a sensitivity of response to various ground motion and structural modeling parameters for systems of representative complexities (degree of redundancy, irregularity and so on), structural systems and materials as well as target performance ranges. Categories for which various techniques for treating uncertainty are suitable should be identified. This is a long term program involving research and directed studies.

3. Basic research and directed studies are needed to assess the practicability and effectiveness of various methods for achieving the desired level of reliability.

Recommendation

One of the objectives of performance based design methods is to manage risk in a consistent and understandable manner. Thus, subjective methods for imposing safety margins (Alternative 1) should be avoided unless verified empirically. Alternative 2 will provide insight into the factors controlling the performance of structures and the ability of various theoretical risk management approaches to achieve their desired goal. Alternative 3 will assess the practicability of the most promising of these methods. These efforts need be coordinated with efforts recommended in Issues 4.7 and 4.8.

Issue 4.7: Characterization of Ground Motions for Performance-Based Design

Issue Statement

What characteristics of ground motions should be considered in specifying design earthquakes for performance-based design?

Background

It is well recognized that peak recorded acceleration is not a reliable indicator of structural damage. Other factors, including peak ground displacement, ground velocity, frequency content, input energy, and duration, have been suggested as potentially improved indices. To date, no consensus has been reached on this issue, with the result that design earthquakes are often defined subjectively using *effective* peak accelerations and modified spectral shapes. These ad hoc modifications obscure the relation between input, response and performance. Further complications arise due to special siting conditions; in particular, concern has been raised for the response of structures located on soft soil or near active faults. Another concern is for seismic environments where the earthquake reasonably anticipated during the lifetime of the building differs substantially from the "maximum credible" event. Design issues related to these considerations need to be systematically investigated. Once important ground motion parameters are identified, they can be utilized in regional or national mapping efforts.

Alternatives

1. The complexities of earthquake ground motions and the multitude of factors influencing their characteristics will never be completely understood. As such, it is incumbent on engineers to devise acceptable design earthquakes based on available information, past performance of structures, and design experience. Current methods of establishing the design earthquake can be extended to cover other performance categories.

2. Post-earthquake reconnaissance inspections and detailed investigations provide great insight into seismic performance. Efforts to instrument buildings and document damage should be expanded nationally. Detailed analyses of building performance will help validate analytical models and improve understanding of the structural and ground motion features that influence performance. Buildings suffering little or no damage should be studied as well as those suffering catastrophic damage. In addition to studies of individual buildings, statistical information on regional performance of building stocks should be gathered. These research and directed studies should be activated immediately following major earthquakes and integrated with other activities related to analysis and design.

3. Detailed analytical and experimental studies of the performance of buildings and systems to various types of ground motions are needed to supplement the limited amount of direct earthquake damage data. These studies should identify critical characteristics of ground motions that can be used for regional mapping of the seismic environment and used in structural design. In addition, certain types of motions requiring special design considerations (e.g., near fault and soft soil siting) should be quantitatively identified and investigated. These efforts should build upon realistic estimates of ground shaking at a site. They should be used to identify means of establishing the design earthquake for that site considering building performance expectations. In this regard, existing as well as new (displacement, energy, etc.) techniques for specifying the design earthquake should be considered. This is an important, long term effort requiring coordinated research and directed study by experts in a variety of fields, including seismology, geotechnical engineering and structural design.

4. It is necessary to gather knowledgeable experts from a variety of fields to assess the broader implications of the ground motion parameters found to influence structural performance. Experts from seismology, geophysics, geology, geotechnical engineering, structural design and dynamic analysis should be involved. Of concern is the reliability with which these parameters can be estimated, and a refinement of terms so that ground motion specialists can most effectively help in establishing design earthquakes for performance-based design. This is an important, but short term, directed study.

Recommendation

Attempts should be made to improve our quantitative understanding of what ground motion characteristics are expected at various sites and what their likely effects on structures will be. Alternative 3 is recommended to identify important ground motion parameters that need be considered in design. Alternative 2 is directed at this issue as well but provides important additional real world verification. Alternative 4 is viewed as being important to assess whether the ground motion parameters of importance can in fact be reasonably predicted at present and to improve dialog between the various disciplines involved.

Issue 4.8: Influence of Building System on Performance

Issue Statement

What features of a building system tend to make it inherently safe or vulnerable to seismic effects?

Background

It has been noted following major earthquakes that the performance of a building not designed for earthquake effects is occasionally superior to an apparently similar structure that was seismically designed and analyzed. This observation suggests that some aspects of a structure (e.g., redundancy, symmetry, stiffness, materials, local detailing, etc.) may make it inherently resistant to earthquake effects. This has been accounted for in most building codes (e.g., through, for instance, R_W factors in the UBC), but the categories employed are related to gross system characteristics rather than on quantitative performance considerations (e.g., stiffness or displacement). Furthermore, relatively little is known about the actual earthquake response of certain types of systems (e.g., plywood shear wall structures, steel braced frames, composite moment frames, etc.), because these structures have not been located in the vicinity of major ground shaking and because these systems have not been subjected to extensive experimental or analytical studies. Thus, little experiential information is available upon which to make subjective determination of R_W values.

Recent codes in the U.S. have also attempted to introduce factors addressing irregularities in the structural system. It is generally agreed that such configuration issues are important, but it remains unclear what precise definition of irregularity should be used and what should be done to correct any deficiencies created. All of these issues become more complex when considering

performance goals (as reflected by the continuing technical debate about the adequacy of importance factors and appropriate methods for treating torsional irregularities). The interaction of the structure with nonstructural components, with foundation and supporting soil, and with adjacent structures also have important, but ill-defined effects on performance.
It is desirable to refine the definition of what structural features contribute to response at various performance categories and for different ground motion types. This would lead to a better understood differentiation between design values, to improved knowledge of what should be done to improve performance, and to more uniform performance of different building types and configurations. It would help identify consistent methods to set design values for existing structures, and for structures with limited ductility or using new materials.

Alternatives

1. The current consensus building process is working well and should be continued for performance-based design procedures.

2. Quantitative information on the specific features of a structure that contribute to improved performance is needed. Post-earthquake investigations and coordinated experimental and analytical investigations along with sensitivity and cost-benefit analyses should be employed considering a wide variety of structural systems, materials, configurations and performance goals. Due regard should be placed on existing data. A long term program of basic research and directed studies is needed considering the variety of systems and materials available to the designer.

Recommendation

A coordinated program of research and directed studies aimed at identifying the factors contributing to the seismic performance of various types of buildings appears key to the development of performance-based codes and to improving understanding of seismic response. Without this effort, Alternative 1 is the only one available to the profession. Alternative 2 would also help identify (and evaluate) detailed and simplified design approaches.

Issue 4.9: Selection of Basic Analysis/Design Methods for Performance-Based Approaches

Issue Statement

What are reliable methods for designing structures that satisfy performance objectives?

Background

As indicated previously, most current design methods are indirect in their approach and are based on modified design forces, elastic analysis and prescriptive details considering a single level design earthquake. As a result, the designer cannot easily make a quantitative assessment of performance based on this approach. Various tasks recommended in the issues stated above should result in (a) reliable analytical tools and modeling guidelines, (b) identification of the important structural parameters needed for various performance categories for different structural systems and materials, (c) structural and ground motion factors that contribute importantly to seismic response and performance, and (e) an improved understanding of the response of structures. This information remains to be synthesized to formulate the basis for a new approach to design considering explicitly stated performance goals.

It is desirable to formulate the basic design procedure in a consistent hierarchical manner, such that similar terms, analysis procedures and evaluation criteria are used for new or existing buildings constructed using different types of structural systems and materials. It is similarly important in the design method that the underlying assumptions, and the relation between input, modeling procedures, response, detailing requirements and performance be clearly and easily decipherable by the designer.

Pertinent design issues include (a) identification of when elastic or inelastic analysis methods would be required, (b) the adequacy of equivalent static methods , modal analysis and response time history procedures, (c) establishment of methods for specifying design earthquake (forces, displacement, energy, spectral shapes, etc.), (d) setting criteria for accepting analytical models (2D vs. 3D, required complexity of overall model, parameter selection for modeling structural and nonstructural components, etc.), (e) determining appropriate methods for assessing local performance in yielding structures (proportioning and detailing criteria), and so on. Similarly, issues as to whether a multi-tiered design strategy is necessary when performance goals beyond life safety (e.g., reparability) are being considered or when there is a big difference between the design basis and "maximum credible" seismic events.

Alternatives

1. Continue to use elastic analysis procedures in which forces are modified to account for the desired performance. This may require the development of modified R_W values and additional adjustment factors to assess displacement and/or other response parameters. Development and verification of response modification factors will require sustained long term effort unless addressed solely on a consensus basis.

2. Develop equivalent elastic analysis procedures in which stiffness and damping characteristics of the structure are modified to account for the level of anticipated inelastic action. Research and directed studies will be required to identify appropriate damping and stiffness properties for use with different structural systems and materials for different performance categories and ground excitations.

3. For design purposes, basic research followed by directed studies are needed to assess the ability of static "push-over" analyses to capture the pertinent features of response necessary for performance-based design. In particular, methods need to be established to estimate the displacement to which the structure should be pushed and means for assessing the effects of ground motion duration, cyclic inelastic response on the behavior of local critical regions,

geometric nonlinearities, and other response features not fully modeled in these static pushover analyses.

4. Appropriate nonlinear dynamic analysis methods should be developed to assess the full range of seismic performance. Issues related to the degree of complexity of the model, the confidence that can be placed in results, the number of ground motions that should be employed, and so on need to be resolved on the basis of previously recommended research and studies. Special research and directed studies are also needed to help formulate and evaluate the appropriate design approach for each performance category and building system.

Recommendation

Unless the response of the structure is to be essentially elastic, the need to empirically modify elastic response to estimate inelastic performance parameters makes Alternatives 1 and 2 relatively unattractive. Considerable work needs to be done to develop the background required to develop a code based on Alternatives 3 or 4; however, these approaches provide the designer with a direct indication of expected performance, and are thus preferred.

Issue 4.10: Identification of Simplified Performance-Based Design Procedures

Issue Statement

Can simplified performance-based design methods be developed for certain classes of buildings and seismic environments?

Background

Current design methods often result in structures that perform well during major earthquakes. As a result, it may not be necessary to change our current design methods significantly in order to achieve certain performance goals. Furthermore, it would be unrealistic to expect designers to carry out complex three-dimensional, inelastic time history analyses for each and every structure. It may be possible to simply the design approaches developed in Issue Topic 4.11. These simplified methods should be consistent with the more refined methods (i.e., simplified methods should result in more conservative designs). Questions regarding the minimum level of required analysis, the nature of prescriptive details and suitable methods for specifying the design earthquake need to be established.

A fundamental question is whether a simplified method is acceptable if it destroys the ability of the designer to measure quantitatively seismic performance, even though it achieves its performance objective for the type of structure and seismic environment considered.

Alternatives

1. Develop an *ad hoc* simplified design approach based on professional judgment, available research and existing codes. Emphasis would be on closing loop holes and strengthening particular requirements in current codes. This would be a moderate term directed study.

2. Develop simplified design approaches in a consistent fashion for various materials, structural systems and seismic environments based on the previously recommended investigations and more refined design methods (Issue 4.9). Minimum analysis requirements should be established. This is a moderate term directed study involving broad segments of the research and professional communities.

3. Develop standardized minimum design guidelines and details suitable for non-engineered structures and buildings located in regions of low seismic risk.

Recommendation

Alternative 1 may be desirable for a variety of reasons, but will not likely result in uniform reliability or develop a understanding on the part of the designer of the expected building performance. Alternatives 2 and 3, synthesized from information on seismic performance, analysis methods, structural characteristics and various seismic environments, will most likely result simplified methods consistent with the goals of performance-based design.

Issue 4.11: Verification Studies

Issue Statement

Can performance-based design methods achieve their objectives practically and reliably?

Background

As indicated previously, computer simulation results are only as good as their underlying assumptions. As such, one must logically question the reliability of performance-based design methods unless they are verified and benchmarked against objective data. Many of the preceding analysis and design recommendations have called for comparison of analytical and experimental results. These efforts should be carried out so that the whole performance-based design process is verified, not just particular pieces. This may require systematic testing of members, components and large structural assemblages of building systems constructed using different seismic-resisting systems, various materials and alternate details.

Efforts are also needed to verify and validate the analytical and design methods developed. This may be done experimentally, as well as through simulations utilizing validated analytical methods and models. The degree of modeling refinement required and the accuracy of various analysis methods should be assessed. Cost-benefit studies should be carried out, including life cycle cost analyses, to assess the effectiveness of the proposed design methods. Such methods, when verified, can be used to assess broader regional or national policy issues.

Alternatives

1 Carryout comparative designs based on design recommendations for various structural systems and materials considering different geographic locations. Compare costs of providing performance-based design. This is a moderate term, directed study.

2. Same as Alternative 1, but carry out reliability analysis of the building to assess likely damage during design basis and other seismic events, estimate immediate post-earthquake economic and other costs of seismic response, and assess life cycle costs of performance-based design. This is a longer term effort involving research and directed studies.

3. Supplemental experimental and analytical studies should be carried out to validate fully the design method. Available information should be compiled and evaluated to determine the scope of these supplemental efforts. This effort is a long term, directed study.

Recommendations

Alternative 2 is recommended as it addresses the benefit of providing enhanced seismic performance. Life cycle cost information can be used to address important public policy issues related to post-disaster aid, insurance and minimum code requirements. Alternative 3 is important to fill in gaps and demonstrate the viability of performance-based design.

Issue 4.12: Educational and Training Issues

Issue Statement

How can the profession be aided in implementing performance-design methods?

Background

Performance-based design requires a new way of thinking about seismic design. The designer needs to visualize the kind of performance desired and then select and design a structure that can achieve this vision. Facilitating implementation of a performance-based code requires user friendly analysis and design tools to visualize and quantify performance. It also requires training about the concepts involved and easy access to information.

The ability of designers to locate and acquire information can be greatly streamlined. Development of knowledge-based systems and information-on-demand concepts for seismic design would greatly reduce professional resistance to implementation. Similarly, greater emphasis can be placed on workshops and seminars. Sponsors of research and directed studies should stipulate more aggressive dissemination efforts.

Efforts should also be undertaken specifically to facilitate training of professionals. To supplement conventional training methods, it is desirable to develop tutorial style handbooks with detailed examples indicating alternatives available to the designer in various situations, and the consequences of these design choices on performance.

Alternatives

1. Current information dissemination mechanisms through technical publications, professional conferences and so on should be intensified.

2. Design handbooks, manuals and tutorials should be developed based on new knowledge and specific case study examples in order to help train design professionals and others related to the analysis and design issues involved. Electronic, interactive and multimedia formats should be investigated. This general activity is viewed as an important aspect to implementation of performance-based design procedures. It should involve broad professional participation in defining required content. This is a directed study task, though it will involve researchers and practitioners from a broad range of specialties.

3. Special efforts should be undertaken to improve the dissemination of available information. This would include facilitating the location of information and its on-demand delivery. In addition, the task should include development of summaries and evaluations of available information on a variety of topics. Use of knowledge-based systems as well as modern telecommunication and data base management systems should be strongly considered. This is viewed primarily as a directed study project.

Recommendation

While implementation of various performance-based design methods can be encouraged through various economic and legal incentives, it appears that it is necessary to make its adoption easy for the practicing professional. This can be done through the development of user friendly computer aided design and analysis tools, and extensive programs of education and training. The effectiveness of these training and information dissemination mechanisms needs to be regularly evaluated and improved.

ISSUE PAPER #5

Geotechnical Engineering and Performance Quantification of Foundations

by

Ricardo Dobry

5. Geotechnical Engineering and Performance Quantification of Foundations

5.1 Introduction

The importance of geotechnical issues in the seismic performance of buildings has been clear for many years, especially in relation to site amplification of ground motions and the effects of liquefaction and ground failure. The first country where this became apparent and systematic efforts were developed to incorporate geotechnical considerations in seismic design procedures and codes was Japan; this was prompted by a combination of frequent earthquakes and of many developed areas having poor soil conditions. By the 1960s, Japan and other countries had introduced into their seismic building codes soil factors as part of the calculation of base shear. In the United States, and despite experiences such as the 1906 San Francisco earthquake where soil effects were a first order contributor to damage, change was slower. This was influenced by the relatively good soil conditions in the Los Angeles area, where much of the seismic instrumentation and code developing efforts were concentrated. Soil S factors and soil structure interaction recommendations were included in 1978 in the ATC 3 project and the Unified Building Code, and have been present since in various forms. These S coefficients were independent of level of shaking and applied only to the long period range. Experience from several earthquakes including Loma Prieta in 1989, as well as a better understanding of the main parameters controlling the soil amplification phenomenon, have recently triggered a consensus proposal through NEHRP and SEAOC, where site coefficients F_a and F_v are defined for both the short and long period ranges, respectively, and these coefficients are made functions of both site conditions and level of shaking. Both the old S factors and the new F_a and F_v factors are intended to quantify site amplification of elastic spectral values only, with any nonlinear structural effect covered by the response modification factor R. Also, the fact that ground motion duration is generally longer on soil than on rock is not included in these factors.

Progress in developing procedures to evaluate the effects of liquefaction and ground failure, and to design against them, has been even slower than for site amplification. Related code provisions when they exist are often vague and qualitative, and they are limited by the state of the art which until very recently could predict only the occurrence of liquefaction, but not its effects. This has changed dramatically in the last 5 to 10 years, due mainly to intensive research efforts in Japan and the United States. These efforts have included especially the use of air photos before and after earthquakes to evaluate permanent ground displacements due to liquefaction and lateral spreading; accumulation of much new information on ground failure and its effects on constructed facilities from case histories, field and laboratory testing, and analyses; as well as a number of joint U.S. Japan projects and meetings. It is interesting that although this U.S.-Japan cooperation (done mostly through NCEER) has so far focused mainly on effects of liquefaction on buried pipelines and other lifelines more than on buildings, it has produced the most relevant and useful information available on ground deformation for all kinds of structures.

Table 5.1 summarizes the issues considered in this paper. Issues 5.1 and 5.3 are self explanatory. Issue 5.2 includes all effects associated with structural forces rather than with free field phenomena, such as consideration of soil structure interaction in the dynamic modeling of building performance, dynamic bearing capacity failure, and foundation failure due to soil liquefaction. Therefore, site remediation is considered mainly as part of Issue 5.2, while recognizing that it also affects the other two issues.

Before addressing individually the issues of the table, a couple of general comments are in order.

Performance of the foundations and of the rest of the building, while closely related, are somewhat different subjects. The difference relates to the larger role of the soil and thus of the geotechnical engineer in the case of foundations. Also, there are all kinds of combinations, even when soil effects are important. Both foundations and buildings may fail beyond repair due to liquefaction-induced lateral spreading (e.g., Marine Sciences Laboratory in Moss Landing, Loma Prieta 1989). The building may fail due to site amplification without the foundation soil and the foundation itself being affected (e.g., buildings in Caracas 1967; Mexico City 1985). The foundation soil may liquefy and fail, with the building tilting as a whole, but with the building and its foundations remaining structurally intact (buildings in Kawagishi cho, Niigata 1964). Or, a pile foundation may be badly broken without the building being much affected, and in fact continuing to function without even noticing that there had been a generalized failure of the foundation for more than 20 years (NHK building, Niigata 1964).

Advances in all three issues of Table 5.1 will require close cooperation between geotechnical and structural engineers. This is obvious in soil-structure interaction Issue 5.2. But even Issues 5.1 and 5.3, which have been investigated so far to a large extent as free-field phenomena by geotechnical engineers and earth scientists, will require active participation of structural engineers as the focus switches to performance.

Table 5-1: Summary of Issues in Geotechnical Engineering

5.1 Modification of Free Field Ground Motions by Local Site Conditions

5.2 Consideration of Soil-Structure Interaction Effects on Foundation and Building Performance

5.3 Determination of Permanent Ground Deformations in the Free Field and Their Effects on Foundation and Building Performance

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Issue 5.1: Modification of Free Field Ground Motions by Local Site Conditions

Issue Statement

To define the modification of free field rock ground motion characteristics affecting building performance by local site conditions.

Background

The issue statement above brings about immediately the main problem we face, which is that we have not yet defined the characteristics of ground motions affecting building performance. This is part of the scope of Issue 4, and it also affects Issues 1, 6, and 7. Once this definition is available, geotechnical engineers and seismologists, with the help of structural engineers, should work toward defining how local site conditions modify these characteristics.

The problem is not trivial and involves further development of the state of the art of predicting round motions on soil. It is clear that in addition to the intensity and frequency content of the ground motions now considered for better or for worse through elastic response spectral ordinates the duration characteristics of the ground motions are also important to building performance. Duration is not considered in current seismic codes, neither when defining the rock ground motion parameters A_a and A_v, nor when specifying the soil factors (old S factors, or new F_a and F_v). Furthermore, available site response analysis techniques (typically 1D nonlinear or equivalent linear programs such as SHAKE) used both to help develop soil factors in seismic codes, and for site specific studies, predict the same duration for soil than for rock. We know that this is not true from actual records, and that there are other effects not considered by these programs which tend to increase significantly the duration on soil. Until now we have not worried very much about this, because the purpose so far has been to evaluate amplification by the soil of elastic response spectra, which are little affected by duration.

However, this changes when we start addressing building performance in terms of nonlinear response and accumulated damage. And here is where prior guidance from structural engineers becomes a must. Should our modeling focus on the total energy of the ground motion defined in a specified way? Or on the duration in seconds? Or on number of equivalent cycles for a given period? Or something else? Or a combination of the above? A simple characterization of ground motions for building performance including duration, based on a small number of parameters and/or curves, needs to be defined. These parameters or curves could then be mapped for rock or stiff soil, and then modified to account for other local soil conditions (and also for topographic effects).

Another route is to ask seismologists and geotechnical engineers to get together and to generate suites of "best estimate" free field acceleration time histories, for selected combinations of seismic regions, magnitudes, distances, and site conditions. These time histories could then be used by structural engineers for generic studies of building performance. This seismological geotechnical engineering effort will most probably require some further development of the state of the art.

Recommendation

It is recommended that a workshop be convened with participation of geotechnical and structural engineers and seismologists. This workshop will use as a starting point the conclusions of the current effort vis à vis characterization of ground motions for building performance including duration aspects, and will focus on how to evaluate modification of these characteristics by local site conditions. The workshop will be assigned three tasks: (i) to define a methodology to obtain realistic acceleration time histories for several selected combinations of seismic regions, magnitudes, distances and site conditions; (ii) to delineate a simplified procedure for modification by the site of main parameters of ground motions important to building performance; and (iii) to define the corresponding development or research tasks that may be needed to accomplish objectives (i) and (ii).

Issue 5.2: Consideration of Soil Structure Interaction Effects on Foundation and Building Performance

Issue Statement

How to model the foundation system in nonlinear analyses of building performance.

Background

This is a complex issue which is far from being solved. A complete scheme would involve defining for each foundation element a set of nonlinear load deformation curves (for vertical and horizontal loading, and for rocking and torsional moments, plus the corresponding cross couplings), all the way to failure, and with incorporation of additional nonlinearities resulting from foundation uplifting; plus definition of cyclic loading unloading rules for these nonlinear springs as well as addition of appropriate dashpots to account for radiation damping. Soil densification and liquefaction under or around the foundation may complicate things even more. Evaluating the effect of site remediation on these nonlinear springs and dashpots is also important.

Some pieces of the puzzle have been solved and have been applied in simplified methods incorporated into seismic codes and guidelines. Small strain stiffnesses and material/radiation dashpots are available for both shallow foundations (including a variety of shapes and embedments) and piles, as a function of the shear modulus (G), or Young's modulus (E), of the soil. These small strain solutions apply to uniform soil deposits and to some simple layerings; computer programs are available for more complicated soil profiles. While these solutions, developed mainly for machine foundations, are frequency dependent, the foundation stiffnesses typically don't vary much for the low frequency range of interest in earthquakes, and in general the corresponding static stiffness can be used to define a frequency independent spring. These elastic solutions have also been used for shallow foundations at increasingly higher levels of shaking inducing larger cyclic soil straining and nonlinearity (but still far from failure), through an equivalent linear approximation in which the modulus G or E of the soil is decreased to make it consistent with the level of seismic strain induced in the soil near the foundation.

This equivalent linear approach is used in the current NEHRP recommended seismic provisions to increase the period and reduce the base shear of buildings on mat foundations as a result of soil structure interaction. Guidelines for the seismic design of highway bridge foundations published by FHWA in 1986 include use of the equivalent linear approach for evaluating the stiffnesses of shallow embedded footings. Viscous foundation dampers representing both radiation and material energy dissipations are also selected at the modal frequencies of the bridge and contribute to the modal dampings. In this FHWA procedure, the seismic stability of the footing is separately checked through estimates of the corresponding ultimate capacities; this is done by means of bearing capacity and other limiting equilibrium solutions. Guidelines for uplifting, liquefaction and settlement under the foundation are also provided.

More recently (1993), a draft proposal for shallow footings has been circulated as part of the ATC 33 effort for retrofitting of existing buildings. In this proposal, three uncoupled elastoplastic springs are proposed for each footing and a given component of ground shaking: for vertical, horizontal and rocking, respectively. The corresponding elastic stiffnesses are obtained with the equivalent linear method, while the plastic yielding plateaus are determined from limiting equilibrium solutions or, in the case of vertical capacity, by multiplying the allowable bearing capacity by a reasonable safety factor (typically 2 or 3). When appropriate, uplifting of the footing under rocking moment is incorporated by assuming a bed of elastoplastic vertical Winkler (purely compressive) springs under the footing, and computing the corresponding moment rotation curve, which then replaces the elastoplastic rocking spring mentioned above. Therefore, this ATC 33 work addresses the problem of generating realistic nonlinear foundations springs necessary for nonlinear static analyses of the structure. However, cyclic loading and the associated question of how to incorporate the material soil damping, as well as the energy dissipation arising from radiation damping in the soil, needed for dynamic analyses, are not considered. Research is now under way at NCEER, sponsored by FHWA, to develop simple rules to incorporate material and radiation soil damping into seismic analyses of bridges.

The situation for pile foundations is more complicated than for shallow footings. Seismic codes typically include provisions defining structural requirements for the top part of the pile and on the connections between pile and pile cap. The FHWA guidelines for bridges mentioned above include recommendations for determining the stiffness matrix of the pile head for both individual piles and pile groups using equivalent linear or nonlinear methods, and based on a beam on elastic foundation approach utilizing mainly p y and t z curves along the piles. Separate recommendations and procedures are specified for rotational stiffness of pile groups, pile batter, liquefaction, pile group settlement, uplift of a pile in a group, and pile cap stiffness. No proposal for piles is yet available from ATC 33. Some critical and unsolved problems include: (i) the contribution to stiffness and capacity of the pile cap; (ii) the effect of the uplift tendency of the piles under the periphery of the structure due to a high seismic overturning moment, with the corresponding load transfer to the inner piles, and the interaction between this uplift and the pile cap which is very sensitive to the type and quality of the pile/cap connections; and (iii) the modeling of pile foundation damping. Research on these three subjects is currently underway at NCEER with FHWA support.

Clearly, the issue is evolving rapidly, with a number of unsolved problems which will require additional research, in areas such as damping, pile foundations, site improvement, and others. Centrifuge model testing may be useful for some of these problems. Close cooperation between geotechnical and structural engineers will be necessary throughout.

Recommendation

It is recommended that close attention be paid to the upcoming ATC 33 recommendations of nonlinear springs for different types of shallow and deep foundations of existing buildings. A small working group of structural and geotechnical engineers should review those recommendations from the viewpoint of nonlinear dynamic analyses of performance of new and existing buildings. This group should also: (i) modify the ATC 33 recommendations if necessary; (ii) supplement them with loading/unloading and damping rules as needed for dynamic nonlinear analyses; (iii) add guidelines in other areas deemed important; and (iv) identify subjects that need further research/development, with indication of the general features of the corresponding projects. A document should be prepared by this working group and discussed in a workshop composed mainly of geotechnical and structural engineers. Follow up by the same or a different working group will be necessary after the workshop until these projects are completed, with the final result being a set of guidelines to realistically model various types of foundation in dynamic nonlinear analyses of performance of new and existing buildings. Before these guidelines are released, typical representative buildings should be selected where soil structure interaction may be important, and actual calculations should be performed using the guidelines to verify them; these sample calculations should be published together with the guidelines.

Issue 5.3: Determination of Permanent Ground Deformations in the Free Field and Their Effects on Foundation and Building Performance

Issue Statement

How to estimate permanent ground deformations in the free field at the site, and how to determine the effects of these deformations on the performance of the foundation as well as of the rest of the building.

Background

There are several relevant aspects here.

First, there is the question of the source of the ground displacements. Vertical and horizontal displacements may have a tectonic origin, in which case the prediction of free field ground deformation is mostly a geological seismological issue, which has been studied and seems to be reasonably understood. California has a setback regulation near surface fault traces related to this. On the other hand, once the ground deformation at a building site has been established, the question of determining its effects on foundations and buildings should not depend on the origin being faulting, liquefaction, or other. Other sources include compaction settlement of loose cohesionless soils, lateral spreading due to liquefaction, and failure of nearby slopes or retaining structures. These sources may sometimes combine; for example, the vertical ground displacement is often the sum of tectonic and compaction contributions. In what follows, the focus is on compaction settlement and lateral spreading, which are the major causes of building damage due to ground deformations.

Second, the discussion must branch out depending on: (i) horizontal (lateral spreading) or vertical (compaction and lateral spreading) displacements; (ii) type of horizontal ground straining (compression, extension, shear) and its relation with the vertical shear ground strain induced by relative vertical displacements; and (iii) type of foundation (spread footings, mat, piles) and its horizontal and vertical dimensions. A key concept here is that the ground straining (or relative ground displacement for a given horizontal or vertical distance) is the main factor affecting performance rather than the absolute displacements. And third, if a reliable prediction can be made of relevant free field ground straining under the building, this has to be translated into evaluations of foundation displacements and damage and of building performance.

The current state of practice for seismic design against ground deformations, including code specifications, is poor. It is essentially restricted to Seed and Idriss' SPT based method and other similar procedures to predict triggering of liquefaction (but which do not address ground deformations or other consequences of liquefaction, and thus are inherently conservative), the Tokimatsu Seed and other similar methods to predict compaction settlement, and sound but mostly qualitative recommendations such as the need to tie individual spread footings.

The state of the art is changing very rapidly, varies greatly from poor to quite good depending on the case considered, and is starting to have an increasing impact on the state of practice. The two cases where geotechnical engineers are now ready to predict with some confidence free field ground relative displacements to be used as input in evaluating damage to the foundation/building, are: relative settlements due to compaction of granular soil layers where the thickness or density of the layer changes under the building, which affect shallow foundations; and relative horizontal displacements with depth due to lateral spreading, which affect deep foundations. These free field displacements can then be used as input for a static nonlinear structural analysis to determine effect on performance. Except for these two cases, where immediate joint work between geotechnical and structural engineers in analyzing performance would be most beneficial, the situation is generally hazier and more empirical. There are techniques that can predict horizontal surface absolute ground displacements due to lateral spreading within a factor of about two, but not the ground straining or relative displacements, and we have empirical observations by Youd on ground displacement thresholds of repairable and irreparable damage for certain types of foundations. Patterns of horizontal ground straining obtained from air photos are being studied and have proved very useful for evaluating damage to extended facilities such as buried pipes. These patterns may perhaps be useful for analyzing large buildings, especially those built on mats, but the observed random variations in ground displacement over distances of the order of dozens of feet will probably dictate a probabilistic approach to the analysis of regular buildings and spread footings.

Another aspect where the SOA is quite poor is in understanding the effects of site improvement on ground deformation and building performance. A reason delaying progress in this important issue is the difficulty of generating enough case history information for the development of empirical correlations such as done for natural grounds. Centrifuge model testing of soil and soil structure systems with and without ground improvement is a promising new tool in this area.

Recommendations

There are two recommendations.

The first is to identify those areas where the situation is already ripe for developing reliable analytical methods and engineering recommendations relating ground deformation and building performance. Possible candidates include ground deformation due to faulting, vertical settlement due to compaction, and effects of vertical variation of horizontal displacement due to lateral spreading on deep foundations. In these areas, small combined structural geotechnical engineering teams could do the job, perhaps with some limited additional development and focused research.

The second is to mount in the building performance area a research and development United States Japan effort similar to that already going on in the buried pipes area. This would be a natural continuation to the buried pipes effort and would keep the momentum going, with the focus now on buildings. Study of effects of site improvement could be one of the tasks charged to the group. If well organized, this new effort should produce in a short time period (a few years) a number of new and reliable methods for the evaluation of building performance in the presence of seismic permanent ground deformations.

ISSUE PAPER #6

Performance Quantification of Structural Elements and Systems

by

James O. Malley

6. Performance Quantification of Structural Elements and Systems

6.1 Introduction

Materials used in structural elements for new construction primarily consist of structural steel, reinforced concrete, reinforced masonry, and wood. Composites of these basic materials have also been used, and other recently developed materials (for base isolation or passive energy dissipation, e.g.) have also been proposed and applied in a small number of applications. These materials are used to form the basic structural elements: slabs, beams, columns, joints, braces, walls, and foundations. These elements are combined in forms such as moment resisting frames, braced frames, shear walls, etc. to provide a complete system for resisting all of the forces and actions (dead, live, seismic, wind, etc.) which are reasonably expected to be experienced by the structure.

Structural design of the wide variety of buildings which are constructed is typically based on specific calculations based on present local building code requirements, or on prescriptive requirements for typical applications (Conventional Construction Procedures for light-frame wood construction, e.g.) that do not require complete engineering design. In either case, the proportion of structural elements and systems and the details of construction are not presently directly related to the explicit seismic performance goals.

In a performance based design procedure, various limit states of the materials, elements and systems should be defined as they relate to the various performance goals for a structure. Appropriate methods for measuring the limit states at the material, element and system levels must be developed. Procedures for explicitly translating measured limit states between the various levels (How does attaining a specific limit for a structural material translate to the element and/or system levels?, e.g.) are required. Engineering procedures for achieving the expected limit states at the various levels and provide the structural performance must be developed.

A complete performance based procedure for seismic design would likely have a basis that applies for all structural materials, elements and systems. It is also likely that such a basis would at least partially applicable for both new construction and also the seismic rehabilitation of existing buildings, although there are significant differences between these two areas which would need to be addressed. It is probably necessary that the many of the methods be nonprescriptive in nature, since new and improved procedures will continually be developed. More prescriptive procedures may be possible for specific levels of performance and/or types of construction. How nonprescriptive methods can be incorporated into a building code format in the existing legal and regulatory climate is not clear.

Table 6-1: Summary of Issues in Performance Quantification of Structural Elements and Systems

6.1 Limit States of Structural Materials: How should the various limit states of structural materials be defined as they relate to the performance goals of the structural elements, systems and ultimately the building?

6.2 Main Structural Elements Controlling the Performance of Different Structural Systems (Traditional and Innovative): What are the main structural elements of the different structural systems currently in use (traditional systems) as well as of the innovative structural systems (such as those based on the use of passive control of structural response)?

6.3 Limit States of Structural Elements and Systems: How should the various limit states of structural elements and systems be defined as they relate each other and to the performance goals of the building?

6.4 Needed Mechanical Characteristics of Typical Structural Elements: What are the main mechanical characteristics that can control the seismic response of typical traditional structural elements?

6.5 Needed Mechanical Characteristics of Innovative Structural Elements: What are the main mechanical characteristics that can control the seismic response of innovative structural elements?

6.6 Relationships Between Global and Local Performance: What are the relationships between the global parameters of the entire structural system of the building and the corresponding response parameters of the structural elements?

6.7 Performance-Based Seismic Upgrading of Existing Buildings: Can the methodology developed for performance based seismic design of new buildings be applied to the upgrading (rehabilitation) of existing buildings?

6.8 Incorporation of New Information into Design Specifications: How can procedures for defining and achieving performance goals for structural materials, elements and systems be incorporated into design specifications (Building Codes)?

Issue 6.1: Limit States of Structural Materials

Issue Statement

How should the various limit states of structural materials be defined as they relate to the performance goals of the structural elements, systems and ultimately the building?

Background

Materials used in structural elements for new construction primarily consist of structural steel, reinforced concrete, reinforced masonry, and wood. Composites of these basic materials have also been used, and other recently developed materials (for base isolation or passive energy dissipation, e.g.) have also been proposed and applied in a small number of applications. These materials are used to form the basic structural elements and systems which comprise the building.

Based on laboratory tests of the various structural materials, various limit states can be defined. For structural steel, limit states for elastic response, yielding, strain hardening, fracture, elastic buckling (local and global), inelastic buckling (local and global) ductility, toughness, low cycle fatigue, etc., can be identified. For reinforced concrete, the limit states might include elastic response, cracked response, yielding of steel prior to concrete crushing, spalling of unconfined concrete, crushing of concrete, buckling of reinforcement and fracture of reinforcement. Similar limit states might be applicable for reinforced masonry. For wood, the limit states might include elastic response, fiber yielding, fiber fracture, fiber crushing, etc. Composite and recently developed materials would need similar limit state definitions. The protective value of base isolation or energy dissipation elements on other elements of the structure would need to be recognized. Note that for all of the limit states listed above both stiffness and strength parameters must be identified in order to completely address the necessary information.

The material limit states described above can in general be defined on the basis of local fiber strain and/or stress, with fairly reliable accuracy. Translation of these material limit states to the limit states of structural elements, systems and finally buildings becomes exponentially more complex and difficult at each level farther removed from the material (identifying system response from material limit states is more difficult than elements response, etc.). For example, the knowledge that there is cracking in a reinforced concrete shear wall is not sufficient alone to define the limit state or performance of the wall element without knowledge of the type of cracking (shear, flexural, coupling beam, etc.), extent of cracking, size of cracks, and reinforcement distribution and detailing. It would be even more difficult to define the limit state of the structural system based on the knowledge of cracking in a concrete shear wall, since that response depends and a myriad of other factors such as configuration, overstrength, redundancy, etc.

It appears, therefore, that it is necessary to develop a progression of procedures from the material to the element, to the system and finally to the building level in order to transfer information related to material response to building performance. It is critical then, to develop reliable methods to develop the first step in this continuum; translating information related to the material limit states to the limit states and performance of structural elements. The limit states of the structural materials and each type of structural element must be identified and the parameters which control the relationship between the material limit state and the element response must be calibrated. This information must be available in forms which are easily developed and used by the designer for the various conditions encountered.

Note that in design, the procedure is iterative, since initially the desired building performance is defined, a preliminary sizing phase is performed, the building is analyzed to determine if the elements can act to meet the intended building performance goals, necessary modifications are made and subsequent cycles are done until the performance goals are met. As a result, transfer of information as described above must take place in both directions (from material response to building performance and vice-versa) throughout the design process.

At levels of performance which imply structural damage in the design earthquake, (life-safety, limited structural damage, etc.) the problem of relating material limit states directly to structural performance is exceedingly difficult. In some cases, it would seem that fairly simple material limit state rules could be developed for the levels of performance which imply little or no structural damage (serviceability, no structural damage requiring repairs), such as elastic response in steel structures, cracking beyond a threshold limit which can be epoxy injected in reinforced concrete, etc. with presently available analytical techniques. Even in these cases, a set of defined limits and method of translation between the material limit state and element limit state and performance must be available.

Alternatives

1. Identify complete rules for material limit states based on fiber strains. Develop fully integrated analytical packages which evaluate element fiber strains throughout the response, which include rules for translating fiber strains into building performance, and vice-versa.

2. Identify complete rules for material limit states. Develop models to reliably translate material limit state rules to the various element limit states and performance (hysteretic load-deflection curves, e.g.). Incorporate models into analytical packages for structural analyses, that have developed rules related to building performance.

3. Identify complete rules for material limit states. Identify performance goals for which material limit states and element performance can be clearly defined and incorporate into presently available analytical structural packages.

Recommendation

Alternatives 2 and 3 are recommended. Alternative 3 can probably be incorporated in some cases with moderate research and effort, through collection and synthesis of available information, but only addresses a portion of the performance levels. Alternative 2 is necessary to address the remainder of the performance levels, and will require collection and synthesis of available material and element information, the development of a list of the areas of knowledge gaps, and analytical and experimental research to fill in the knowledge gaps.

Issue 6.2: Main Structural Elements Controlling Performance of Different Structural Elements

Issue Statement

What Are the Main Structural Elements of the Different Structural Systems Currently in Use (Traditional Systems), As Well As Innovative Structural Systems Based on the Use of Passive Control of the Structural Response?

Background

The elements for traditional superstructure systems include the following:

1. **Moment Resisting Space Frames** - Slabs, Beams, Columns, Beam-Column Joints (Connections and Joint Panels), Collector Members.

2. **Concentrically and Eccentrically Braced Frames** - Slabs, Beams, Columns, Struts (Braces), Beam-Column Joints and Strut (Brace) Connections, Collector Member, Shear Links (Eccentrically Braced Frames only).

3. **Single and Coupled Structural Walls** - Slabs, Collector Members, Walls (Panel and Edge Members), Coupling Girder (Coupled Walls only).

4. **Main Structural Elements for Innovative Systems** - Aside from the elements indicated above for the traditional structural systems, the following additional elements are used or have been proposed for the key elements that will control the seismic response of the entire superstructure.

    - ***For Moment Resisting Frame Systems***
        - Use of special connections at the ends of the beams to dissipate energy through friction in the case of steel moment resisting space frames.
        - Use of special energy dissipation devices (yielding metals, friction and viscoelastic or viscous dampers) at certain proper locations of the beams that are used to connect the beams with tree columns.
        - Addition of braces (diagonal, X, chevron) with energy dissipation devices, either at the end of their connections with the beam-column joint or at the dissipation devices can be of the yielding metals, friction or viscous dampers.
        - Addition of shear walls connected to the upper beams through energy dissipation devices.

    - ***For Braced Frame Systems***
        - Addition of energy dissipation devices at end of the braces or where they cross in case of X bracing, which will control the maximum axial forces acting on the braces, as well as dissipating energy.

- ***For Structural Wall Systems***
    - Addition of energy dissipation devices at each story between the upper end of the wall and the bottom of the floor beam.
    - In case of coupled walls, energy dissipation devices can be added to the coupling girders.

The key issue to consider in relation to the structural elements is proper selection to obtain the intended seismic performance of the entire structural system. Considering the above different structural systems and their corresponding structural elements, the following alternatives could be considered.

Alternatives

1. For Moment Resisting Space Frames:

    A. Traditional beam elements designed by proper consideration of stiffness and strength (selecting proper locations of critical regions for plastic hinging.
    B. Traditional beam elements with special energy dissipation devices added at certain proper locations.
    C. Traditional beam element with viscous dampers added at certain proper locations.

2. For Braced Frame Systems:

    A. Conventional Concentric Bracing of various types.
    B. Eccentric Bracing at the beam element.
    C. Any type of bracing introducing friction devices at the connections.
    D. Chevron type of bracing with knee energy dissipation devices at the ends of the braces.
    E. Any type of bracing using linear viscous damping material at one end of the braces.
    F. Any type of bracing introducing energy dissipation devices between the end of the braces and the beam.

3. For Structural Wall Systems:

    A. Use of traditional single or coupled walls.
    B. Use of single walls, with the addition of energy dissipation devices (at each story or at certain stories) between the upper end of the wall and the floor beam or slab.
    C. Use of special single walls (at each story or at certain stories) where a steel plate connected to the top floor beam will move through viscous material contained in the wall.
    D. Use of coupled wall where coupling is provided through special energy dissipation devices.

Recommendation

Traditional systems, such as Alternatives 1.A, 2.A, 2.B, and 3.A have proved to be reliable for providing life safety or limited damage control with proper design and detailing. For added protection, and where functionality after the design earthquake is desired, the use of energy dissipation devices based on viscoelastic elements is highly recommended, i.e., Alternative 1.C, 2.E or 2.F, using viscoelastic dissipators and Alternative 3.C or 3.D. Because of lack of sufficient data regarding the effect of aging and temperature in the behavior of the viscous materials for the short-term application of the use of energy dissipation devices based on yielding of metals seems to be the most promising solution for immediate practical application.

Issue 6.3: Limit States of Structural Elements and Systems

Issue Statement

How should the various limit states of structural elements and systems be defined as they relate to each other and to the performance goals of the building?

Background

The various types of structural materials are used to form the basic structural elements: slabs, beams, columns, joints, braces, walls, and foundations. These elements are combined into forms such as moment resisting frames, braced frames, shear walls, etc. to provide a complete structural system for resisting all of the forces and actions (dead, live, seismic, wind, etc.) which are reasonably expected to be experienced by the structure.

In a performance based design procedure, the limit states of the structural elements and systems must be defined. These limit states generally include an initial level of linear elastic response followed by an nonlinear response (yielding or buckling of the element) which eventually leads to the ultimate response ("failure") of the element. A number of nonlinear response and failure modes can be identified for each type of structural element. For example, a steel beam can exhibit flexural or shear yielding, elastic or inelastic lateral torsional buckling, elastic or inelastic local buckling, etc., depending on the composition of the element and the relationship of the loading and support conditions. The type of nonlinear response and failure exhibited by specific structural elements can have important implications on the performance of the system and building.

There is a large amount of knowledge for estimating the elastic response and failure mode and strength of structural elements, most of which has already been incorporated into modern building codes. Incomplete knowledge exists regarding the nonlinear response of most structural element types, especially in high-strain, low cycle fatigue response, and that which is available is cumbersome to use in design applications.

Descriptions of response limit states can also be developed for structural systems, based on the compilation of the element response. Ideally, this compilation would lead to an estimate of system deflection parameters (story drifts, total deflections, velocity, accelerations, etc.) which would then be correlated with desired building performance features. Presently employed estimates of element strength are typically conservative, resulting in an overstrength feature which can become pronounced when elements are combined into complete structural systems. Also, even less reliable information is available related to the correlation of local element limit states and actual building deformations. Widely accepted analytical procedures are not yet available which can accurately predict recorded building deformations at all levels of response. Even beyond this is the assignment of building performance based on system response and deformations.

The availability of reliable information related to the limit states of the various structural elements, including nonlinear response and failure is critical to developing rules for the limit states of structural systems. In addition, reliable procedures for estimating building response parameters such as story drifts and deflections are needed. This information is crucial to developing an ability to identify building performance, especially at the lower levels of performance (life safety, etc.).

Alternatives

1. Develop a complete analytical packages to translate element limit states to building performance.

2. Improve and build on existing knowledge base for nonlinear response of structural elements. Develop analytical packages which can incorporate new information and provide accurate estimates of structural system deformations. Develop rules to translate system deformations local element response to building performance.

3. Developed simplified rules for use as part of a building design procedure based on one of the methods listed above.

Recommendation

Alternatives 2 and 3 are recommended. Alternative 2 should be developed first and implemented for a time before Alternative 3 can be completed. This may take a great deal of time and effort, including research into actual building response in future earthquakes. Once Alternative 2 is completed, it will take a moderate level of effort to develop simplified rules, within a consensus process. It may be possible to develop Alternative 3 for certain classes of buildings at an earlier date.

Issue 6.4: Needed Mechanical Characteristics of Typical Structural Elements

Issue Statement

What are the main mechanical characteristics that can control the seismic response of typical traditional structural elements?

Background

From analysis of the issues involved in the seismic design of new buildings (as well as seismic upgrading of existing hazardous buildings) according to performance-based design procedure, it has been concluded that this is more a problem of deformation (displacement, interstory drift index) and rate of deformation (velocity, acceleration, jerk) rather than strength. Furthermore, from this analysis it has been recognized that the global seismic response, and therefore the performance of a building or any kind of facility, involves the three dimensional deformations of the three dimensional building when subjected to at least the three translational components of the critical ground motions at each of the main levels that need to be considered. While in the case of the design for the performance required at the service levels, for which the entire structural system must remain practically in the linear elastic range, it is possible to solve the three dimensional problem by superposing the solutions of two dimensional problems. This cannot be done in cases where significant inelastic deformations are involved at life-safety level designs, as they are in the case of design for public safety of nonessential facilities.

Assuming that the issue of the quantification of the global performance of the entire structural system of a building has been solved for the necessary response parameters (maximum displacement, maximum interstory drift, maximum velocity and acceleration, minimum strength at first significant yielding, displacement at impending mechanism and ultimate stages, and damage index) at each of the performance levels, the designer has to estimate if by providing the structural system with the maximum ductility it is possible to attain the maximum acceptable damage index according to the expected energy dissipation demanded. Considering that the achievement of the above required values for the global response parameters depends upon the design of the structural members of the entire structural system and of their connections, joints and supports, it is obvious that to carry out such design requires knowledge of the relationship between the adopted or specified values for the global response parameters, and the required values for the corresponding response parameters of the individual members. This relationship is discussed as Issue 6.6, where it is recommended that the ideal solution is Alternative 4, which requires quantification of the stiffness, strength and damage index of each of the structural elements considering the three dimensional actions developed in each of these members by the acceptable three dimensional global deformations of the entire structural system.

The issues that remain to be answered are:

- For what kind of actions (due to seismic excitations and other significant excitations such as those due to gravity) should each of the main structural elements (identified in the discussion of Issue 6.2) be designed, and how should these members be designed to satisfy the local performance requirements that will lead to an entire structural system for the building that will satisfy the desired adopted global performance requirements?

- How can the preliminary design of the structural elements be carried out? i.e., what are the main required mechanical characteristics that need to be quantified in order to properly design (size and detail) each of the structural members so that the entire structural system will respond in accordance with the established desired performance design criteria?

Although the worldwide-accepted philosophy of seismic design hints at three levels of ground motion and performance, for the sake of simplicity in this discussion only the two following levels are considered: Service and Safety.

From the previous discussion, it is clear that for traditional superstructure systems the main members are slabs (diaphragms), beams, columns, beam-column Joints (including connections and panel zones), braces, shear links, coupling girders, structural walls, and collector members. The design of slabs is usually controlled by the strength and stiffness (vertical) required by the service gravity loads, but has to be checked against the effects of the lateral seismic forces acting on the slab plane when it is working as a diaphragm, and it must be determined whether there is a need for a diaphragm chord, diaphragm strut and collector members. The design of the other elements listed above is usually controlled by the requirements posed by the combination of gravity and seismic excitations at the different levels of performance (Service and Safety), and requires consideration not only of stiffness and strength requirements, but also of the control of the response parameters affecting the comfort of the occupants and damage to contents, nonstructural and structural elements (i.e., maximum interstory drift, floor velocity and acceleration, as well as ductility and energy dissipation). To be able to answer the question regarding the kind of actions, one must recognize that the actions and deformations in the structural elements are strictly three dimensional.

At present there are not sufficient and reliable data regarding the prediction of the mechanical behavior of real structural elements under these three dimensional actions, particularly when these elements are allowed to undergo significant damage (inelastic deformations) at the Safety level of performance. To facilitate the seismic design attempts should be made to determine if it is possible that the structural elements can be considered (modeled) as linear structural elements which are subjected only to actions acting in the main plane of the elements. If this is not possible, then can the three dimensional response of these structural elements be obtained by considering as nonconcurrent the actions in each of these planes and then applying some approximate rules for super-imposing these independent effects to estimate their actual three dimensional response (performance)?

Ideally, it would be desirable to consider all of the mechanical characteristics that are needed to understand the performance at both the safety and service levels. However, due to the lack of reliable data, efforts should be made to design the overall structural system properly so that two dimensional procedures can be reliably applied.

The significant mechanical characteristics of the various structural elements that need to be quantified to achieve the desired performance at the service and safety levels. These characteristics include the stiffness, strength, ductility ratio capacity, energy dissipation capacity due to hysteretic damping and hysteretic plastic deformation, and damage index. Columns and selected other elements may be subjected to significant three dimensional effects which must be recognized in the definition of the mechanical characteristics.

The significant mechanical characteristics of the traditional structural elements, as well as the main parameters and the types of actions that need to be considered in the quantification of these characteristics, have been identified and discussed above. While this might be sufficient for developing a non-prescriptive (conceptual) methodology for performance-based seismic design, for prescriptive methods to be used in practice, i.e., for development of practical prescriptive seismic code regulations, it is necessary to give expressions and/or tables and graphs, which will permit the numerical quantification of such mechanical characteristics. To accomplish this for each of the various types of structural elements for each of the performance levels with sufficient reliability requires complete knowledge of the mechanical characteristics and response.

For example, consider all of the parameters in identifying the stiffness of a reinforced concrete beam. These parameters for service levels (elastic analysis) include the effective length between supports, the concrete modulus, cracked and uncracked sections, variation along the length depending on the local bending moment, effects of floor slabs, etc. For safety level design, the calculation of effective secant stiffnesses is also necessary. For reinforced concrete columns, the problem becomes even more complicated due to the three dimensional effects.

Alternatives

1. Identify all of the required mechanical characteristics for the various traditional structural elements and identify the types of actions for which they need to be considered.

2. In addition to the identification process described in Alternative 1, develop detailed specific rules for the quantification of the main mechanical characteristics of each of the traditional structural elements as they relate to the performance objectives.

3. In addition to the identification process described in Alternative 1, develop guidelines for the proper distribution, design and detailing of the various structural elements as they relate to the performance objectives.

Recommendation

Ideally, Alternative 2 would be recommended. This will require substantial time and research effort. Alternative 3 may be an acceptable substitute until all of the necessary information is available.

Issue 6.5: Needed Mechanical Characteristics of Innovative Structural Elements

Issue Statement

What are the main mechanical characteristics that control the seismic performance of energy dissipation devices that are used for passive control of the response of the entire structural system, and how can they be quantified?

Background

The main purpose of using energy dissipation devices is to control the response of the traditional structural systems such that they will not undergo any significant damage or inelastic behavior, or, in other words, so that they perform "elastically." All the dissipation of energy (both damping and hysteretic)) needed to reduce the required elastic strength to the desired level is achieved through the response of these special devices. It is therefore necessary to identify the main mechanical characteristics that control the behavior of the dissipation devices at the various performance levels. For the sake of simplicity, only the use of the following three groups or types of energy dissipation devices are considered herein: yielding of metals, friction, and viscoelastic dampers.

Before starting the discussion of these three groups of energy dissipation devices, it should be noted that another possible solution for controlling the performance of the superstructure system so that its response remains in the elastic range is to control the energy input to the superstructure system through the use of base isolation devices. The implementation of this technique has been widely research and developed to the point that seismic design specifications have been developed. As the application of this technique is confined to buildings with relatively short periods and to be located in firm soil, this technique is not discussed herein.

The mechanical characteristics that will control the behavior of each of the above groups depends on the type of actions (one, two or three dimensional) that will act on them, and this in turn depends on where the devices are located and on how they are designed and constructed. Thus, guidelines should be developed regarding, first, how to select the locations of these devices in the different types of structural systems, and secondly, how to design their shapes. The main mechanical characteristics must also be defined for the various levels of performance.

For metal yielding devices, the mechanical characteristics include the stiffness (elastic, secant and strain hardened), strength (elastic limit, fully yielded and ultimate capacity), ductility ratios, energy dissipation capacity due to hysteretic plastic deformation, and damage index (such as Miner's rules).

Note that as these metal yielding devices (except for the internal damping of the metal and damping in their connections, which are small) do not dissipate energy in their elastic range of behavior, and thus they are not effective devices for controlling the performance at service levels, except for adding some stiffness.

For friction devices, the key mechanical characteristic is the slip force, although knowledge of the load-deformation relationship and long term operability are also required. As with metal yielding devices, these elements do not improve the performance at service levels unless they are used with braces to add stiffness.

For viscoelastic dampers, the damping ratio is the most important characteristic. Damper stiffness, loss factor and temperature effects should also be known.

Once the main mechanical characteristics that control the seismic performance of energy dissipation devices have been identified and the way of quantifying such characteristics has been developed or suggested, the problem that remains is how to incorporate them into the performance based design process of the entire structural system of a building. Alternatives to the solution of this problem are offered below.

Alternatives

1. Develop detailed specific rules for the main mechanical characteristics as well as for their quantification for each of the different types of energy dissipation devices.

2. Develop detailed specific rules as above as well as guidelines for the proper (efficient and reliable) distribution of these devices throughout the entire structural system.

3. Develop above detailed specific rules and guidelines as well as conventional structural seismic design flow charts, including the selection and design of the energy dissipators.

4. Develop general (non-prescriptive guidelines about these energy dissipators and to try to consider all these devices as dampers which have an equivalent viscous damping coefficient according to their energy dissipation capacity.

Recommendation

The ideal solution is offered by Alternative 3, but obtaining sufficient reliable data will require long-term focused research for most of the current available energy dissipators.

Issue 6.6: Relationships Between Global and Local Performance

Issue Statement

What Are the Relationships Between the Required Global Performance or Response Parameters of the Entire Structural System and the Corresponding Parameters of Its Structural Elements?

Background

A number of response parameters such as the stiffness, displacement or drift index, the velocity and the acceleration, as well as the strength, ductility and energy dissipation capacity of the entire system depends on the stiffness, strength, ductility and energy dissipation capacity of its structural elements (intentional and unintentional) and on the connections among these elements, as well as of their supports. Because a real building is a three dimensional multi-degree of freedom system which is subjected to at least six components of the earthquake ground motion, it is clear that the deformations and therefore the actions acting on any structural element, strictly speaking, are three dimensional. There are some structural elements on which, because of their location and sizing, the controlling actions can be considered to be those acting just in their main longitudinal planes (case of beams). But, there are other members, such as the corner columns of a moment resisting space frame, that develop significant three dimensional actions (Bending Moments, Shears, Axial Forces, and Torsion) as consequences of the three dimensional deformations. Thus it can be concluded that the key global response parameter and consequently the key structural element response parameter is the three dimensional deformations. Hysteretic actions in the form of forces (axial and shear) and moment (flexural and torsion), and therefore the required strengths, are consequences of the three dimensional deformations and the stiffnesses provided. Similarly, the required ductility ratios, are consequences of the demanded three dimensional deformations, and of the stiffnesses and strengths provided.

In case the design of the entire system for the life-safety performance objective is based on allowing damage through significant plastic deformation, it is of utmost importance to know or estimate the relationship between the global ductility of the entire system and the local of the various structural members. There are two problems in specifying this relationship. The first is related to determining the type of element ductility definition (fiber strain, curvature, rotation, displacement, monotonic, cyclic, cumulative equivalent to energy dissipation, damage equivalent) used to establish this relationship. The second issue is the proper quantification of the relationship. The global performance depends on the displacement ductility, and the damage index is a function of monotonic displacement and the energy related ductility. Thus, the global ductility should be specified as a function of the damage index. Then this global ductility should be related to the local displacement ductility of the structural element, which depends on its local rotational or curvature ductility. It is well known that the global displacement ductility provided of the entire structural system is less than the story displacement ductility; and that the story displacement ductility is less than the local element ductility.

However, the data available are not enough to recommend reliable quantification of these relationships. Most of the data available are based on study of planar moment resisting frames (Nassar and Krawinkler), neglecting the real three dimensional nature of actual buildings.

Alternatives

1. Continue judging the global performance of the entire structural system on the basis of the required base shear strength and maximum displacement or interstory drift index in the direction of each principal axis of the structure. Because the design is based on elastic analysis, the only important response parameters of the structural elements are the yielding strength and stiffness.

2. Quantify the global performance of the entire structural system through the maximum deformation interstory drift index and in the case of performance for life safety, add the amount of damage through damage function or a damage index in each of the directions of the main axis of the building. As the damage index depends on the global ductility and the energy dissipation, the performance parameters that should be considered for each of the structural elements (intentional and unintentional) and therefore in their design should be the stiffness, yielding strength, and the tolerable damage as functions of the element local ductility and energy dissipation. These terms can be estimated considering only the effects of the two dimensional actions along the main axis of the structural element as obtained through a non-concurrent pushover two dimensional nonlinear analysis.

3. Similar to alternative 2, but considering all the various global response parameters which impose adding extra quantification requirements on the stiffness of the structural members.

4. To quantify the global performance of the entire structural system considering all the various global response parameters considering the three dimensional effects of the 3 components of the ground motion acting simultaneously. Thus, it will be necessary to consider the relationship of all the global response parameters with the stiffness, strength and damage index of each of the structural elements considering the effects of the three dimensional actions developed in each of the members by the three dimensional global deformations of the whole structural system, which in turn requires three dimensional nonlinear time-history dynamic analysis.

Recommendation

The ideal Alternative is 4. However, it is not yet possible to obtain the data needed to quantify reliably the relationship between the global response parameters of the entire structural system and the corresponding parameters of the structural elements considering the three dimensional effects, especially when structural damage is allowed. Extensive, long term research appears to be necessary to provide this data. Thus, Alternative 3 is recommended for practical implementation in the short term.

Note that because at present it is very difficult to develop reliable methods for predicting the relationship between the global structural damage and the local structural damage considering the three dimensional effects, an attractive solution for the life safety performance level is to reduce the elastic response required by these design earthquakes through the use of additional viscous damping, i.e., to achieve energy dissipation in these elements large enough to eliminate the need for significant ductility and energy dissipation in the other structural elements, which causes in structural damage.

Issue 6.7 Performance Based Seismic Upgrading of Existing Buildings

Issue Statement

Can the methodology developed for performance based seismic design of new buildings be applied to the seismic upgrading (rehabilitation of existing buildings?

Background

The mechanical characteristics, and in general all the concepts involved in the performance based seismic design of structural elements, as well as of the entire structural system of new buildings, can also be used for the seismic upgrading of existing buildings. However, there are some basic differences. The most important difference is introduced because for upgrading work it is necessary to initially assess the vulnerability of the existing building (i.e., what are the weaknesses of the existing building regarding the desired performance of such a building?). The uncertainty involved in assessing the mechanical characteristics of the material, of the structural elements and structural systems, are significantly larger than the corresponding uncertainties related to the mechanical characteristics of properly designed, inspected and maintained new construction.

To design the upgrading work, it is necessary to know the resistance- (force-) deformation relationship of the existing building. In general, and particularly in the case of reinforced concrete buildings, a reliable estimation of this relationship is very difficult to obtain, because it depends upon not only the size of the members, but also their detailing and their connections and supports throughout the entire structural system. In the seismic design of a new structure for some desired performance levels, the elements are designed to attain such performance by estimating the relationship between the established global performance and the element local performance. On the other hand, to assess the levels of performance that an existing building can deliver, it is necessary to start by estimating the mechanical characteristics of the material, then of the element, then of their connections and supports, and finally to determine the resulting mechanical characteristics at the different limit states and performance levels that are desired for the building that has to be upgraded. This kind of assessment (vulnerability assessment) for an existing structure should be based on extensive *field work* rather than solely on *office work*, unlike usual practice in the design of new buildings.

Furthermore, after the vulnerability assessment has been completed, the designer is confronted with the problem of deciding how to modify the existing construction (what has to be added and/or how to integrate the existing construction with the reinforced or newly added elements) to achieve the desired performance under different levels of ground motion. It must be recognized that stiffening and/or strengthening old members, or adding new members and integrating their response with the existing old members is work that involves larger uncertainties than those involved in the design and construction of a complete new structural system.

Alternatives

1. Develop a performance based design criteria and procedure for existing buildings separate from that to be developed for new structures. Such a procedure would take into consideration the larger uncertainties involved in the vulnerability assessment of the existing construction and integrate the response of the strengthened or new structural elements and/or structural system with the existing ones.

2. Develop nonprescriptive guidelines on how to modify the performance based seismic design procedure for new buildings when applied to existing buildings. Include modifications to be introduced in the sizing and detailing of the strengthened old elements and/or new structural elements to be added to the existing construction.

Recommendation

Alternative 1 is recommended, but because to develop a reliable new complete descriptive procedure for existing buildings may require significant efforts and the urgent need for having some prescriptive rules regarding how to deal with the seismic upgrading of existing buildings, Alternative 2 may be considered with the understanding that efforts to develop Alternative 1 are also started. Also note that the ATC 33 project is presently addressing the seismic upgrading of existing buildings, including consideration of various performance goals.

Issue 6.8: Incorporation of New Information into Design Specifications

Issue Statement

How can procedures for defining and achieving performance goals for structural materials, elements and systems be incorporated into design specifications (Building Codes)?

Background

Present seismic design specifications (codes) have developed over the past forty years based to a great extent on the physical observations of the response of actual buildings in past earthquakes. For example, major advances in the Uniform Building Code (UBC) were made soon after the 1971 San Fernando and 1972 Managua, Nicaragua Earthquakes. The next generation of seismic building codes will increasingly be based on calculation rather than observation. It is critical that such future codes also be founded on actual building response; advances in analytical techniques should therefore not be fully incorporated into code requirements until there is a broad consensus that they can accurately reflect actual building response to earthquake ground motions. It is also crucial that advances in element detailing requirements which provide ductility continue to be included in future codes until there is conclusive evidence for their relaxation.

The advanced analytical techniques which are envisioned to be at the core of a performance based design procedure, may be extremely difficult to codify in the prescriptive manner of present building code requirements. Obtaining consensus agreement for the appropriate element and system analytical procedures at the different performance levels will be difficult. The codification should be written so that the latest improvements and developments can easily be incorporated. A nonprescriptive approach for the code language implies concerns for consistent enforcement by local building code officials and for liability issues. Some requirements for peer review may be necessary for buildings designed using advanced analytical techniques and performance based design, at least until such time as there is broad consensus and widespread of the procedures.

Prescriptive techniques may still be advisable as a "code minimum" for all buildings, and for all performance for some classes of construction (light-frame wood, e.g.). The incorporation of advanced techniques would be reserved for owners who desire a performance level above the life safety level which is intended to be addressed by the present building codes.

Alternatives

1. Develop a performance based procedure which includes nonprescriptive requirements for advanced structural element and system modeling. Procedure may or may not be intended for incorporation into future code requirements. Require peer review whenever such techniques are utilized.

2. Develop a performance based procedure which includes prescriptive requirements for advanced structural element and system modeling, with the intent that it be incorporated into future code requirements.

3. Maintain building code requirements with prescriptive provisions similar to present format, updating to incorporate performance based improvements as they become available.

4. Develop prescriptive performance based requirements for certain levels of performance and/or classes of buildings which can be most easily be agreed to by the engineering community.

Recommendation

Alternatives 1 and 4 are recommended. Alternative 1 will require a great deal of time and effort to address all of the issues developed, including extensive research and consensus building work. Alternative 4 will be developed in concert with Alternative 1.

ISSUE PAPER #7

Performance Quantification of Nonstructural Components

by

Bob Reitherman

7. Performance Quantification Of Nonstructural Components

7.1 Introduction

The presumption behind the papers prepared for this workshop is that our goal should be to change from prescriptive rules to performance-based methods, which is like discarding etiquette ("behavior prescribed by rule or custom") and relying instead on courtesy. This is not altogether good.

Etiquette is a set of formalized rules of conduct that are supposed to bring about nice behavior. One isn't supposed to reason out how best to achieve the purpose for which a rule of etiquette was devised--one simply starts with the fork on the outside and then one works ones way in toward the plate. Etiquette's rules are encrusted with opaque tradition, their rationale is often unclear, and they are numerous.

Courtesy by contrast is the performance-based way of achieving nice behavior. Tell people the objective is "do unto others as you would have them do unto you" and let them figure it out from there. So far, it looks like etiquette is the underdog in this argument.

Making your children memorize the rule, "Clean up your own place at the table after dinner" is a prescriptive rule of etiquette. This simple-minded convention usually manages to result in the dishes being carried from the dining room to the kitchen. Alternatively, the performance-based principle of courtesy can be tried: "I'm already washing the dishes and putting the food away, so shouldn't you bring your own glass and plate to the kitchen sink?" Based on a multi-year experiment (Reitherman, in progress 1993) the prescriptive approach works, the performance-based one doesn't. Perhaps etiquette has some merit after all.

In the world of nonstructural components, the prescriptive approach is to run aircraft cable up through the stem of a pendant light fixture and tie it off so that if the fixture sways excessively and the mount or stem breaks, it won't completely fall and hurt someone. Putting two 12-gage wires at diagonally opposite corners of a lay-in fixture is a similar convention. Thousands of such fixtures have this simple but effective protective detail. Such prescriptive solutions often appear on construction drawings in a routine way, at least where the Uniform Building Code has been carefully enforced or especially for California public schools. This detail will not be found on the structural engineer's drawings but on the architectural or electrical sheets--an admirable and unusual diffusion of earthquake engineering. Approximately 15% of a building's floor area lies in the "hazard shadow" of these light fixtures: Keeping those items from falling is a significant risk reduction accomplishment. The only problem is enforcement and implementation, which are perennial problems but easier to solve with repetitive prescriptive solutions than performance-based alternatives that by their nature tend to differ from one project to another. Perhaps you will raise the objection that the architect hasn't analyzed light fixture performance in earthquakes and has never bothered to think out the problem from first principles, and that this mindlessly followed prescriptive rule should not be praised. But does it matter? We don't know what all the Latin abbreviations mean that we use so frequently, e.g. "e.g." As long as you know that "e.g." can be used instead of "for example," does it matter that virtually no one knows it stands for exampla gratia? Score a point for etiquette's prescriptive approach.

Suspended ceilings also have their prescriptive rules: Four-way diagonal bracing wires at standard intervals with a vertical compression member, specified gauges of metal T-bars, and other prescriptive rules have been contained in UBC Standard 47-18. When subjected to strong shaking, what happens to such ceilings? They're often damaged, even when the structure remains elastic. In addition, associated ceiling components such as piping are sometimes broken because of nonstructural "pounding" (or "seismic slap" as a non-engineer once termed it). The dynamics related to these pendulum systems of various lengths, plan configurations, and periods of vibration, along with interference by the thicket of electrical-mechanical components stuffed into the ceiling space, lack of an easy way to avoid damage in the areas along the edges, and the fact that the suspended ceiling system was invented without thought of earthquakes and was only later retrofitted to make its performance passable while still accommodating typical installation practice--all these factors are largely ignored or hidden from view of the designer. The code took the approach of saying it is sufficient to memorize the rules of etiquette, the conventions, rather than to use the principle of courtesy and reason out what is necessary to assure good behavior in a particular circumstance. Maybe etiquette has its limitations.

Because of the fact that there are so many nonstructural components, and many of them are inevitably introduced into a building without benefit of structural engineering counsel, we would be foolish to put all our trust in the approach of specifying the general objective and then trusting the design and construction industries to tend to all the necessary details. In California, every water heater sold in the state now comes packaged with a brochure on "Earthquake Bracing of Water Heaters for Residential Use," (Article 8, Sec. 19210, Chapter 2, Part 3, Division 13, Health and Safety Code). Unless we expect structural engineers to make house calls every time a plumber installs a water heater, the prescriptive approach is the only possible alternative. On the other hand, while we can raise the average level of quality of nonstructural protection by ensuring broader compliance with a relatively small number of prescriptive rules, we will never elevate the field beyond its rather primitive state if we don't focus the attention of designers on rationally defined performance objectives and give them some leeway in devising ways to meet those requirements. Any resolution of this issue that relies on only one or the other of these approaches is bound to be wrong.

The above examples concern components that are more sensitive to their internally generated inertial forces than the deformation imposed on them by the behavior of the structure. For the imposed deformation problem, don't our codes already use a performance-based approach? For example, the UBC states (sec. 2336 and Table 23-K) that "the design and detailing of equipment which needs to be functional following a major earthquake shall consider the effect of drift" if the facilities are fire stations or even "emergency vehicle shelters and garages." However, compare this performance-based guidance with the fact that it is common to find soft-front-wall fire station structures with standard overhead doors installed without any special detailing to protect their special post-earthquake essentiality. If this principle of seeking good behavior through performance-based precepts is to work the structural engineer must first calculate realistic drifts. (For most analyses--probably the great majority of low-rise buildings such as fire stations--the elastic deflection is surprisingly easily factored up into an inelastic one by multiplying a round integer, representing R, and a round fraction, 3/8, which suggests that either these calculations are only approximate or that earthquake engineers have been fooling us for decades by saying inelastic behavior is a difficult subject). Secondly, these figures must be communicated to the architect. Third, the architect must understand what these calculations of lateral deflections or height/deflection ratios mean. Fourth, the architect must investigate alternative overhead garage door products and, not finding a model that promises to supply specified drift-tolerance in conformance with some testing standard, devises special details to accommodate the amount of deformation the building will impart to this nonstructural component. In this final design stage, the architect will decide a few questions, such as how much bolt slip adds up to, how much give there is in the track, at what point a door will completely jam rather than just stick a little. This introduces numbers and judgments at least as approximate as the engineer's drift calculations.

This thorough type of architectural-engineering solution has been implemented over the past few decades. We know this actually happens because it is documented by papers written by the architects or engineers involved to commemorate these special occasions. More common, however, is the damage to millions of square feet of buildings over the past few decades that would have been avoided or greatly reduced if "engineered architecture" were the rule: Earthquakes have an objective way of conducting a survey to determine what percentage of the veneer, cladding, glazing, partitions, and other nonstructural components have actually been designed to accommodate calculated drifts, UBC sections notwithstanding. Religions have to deal with sinners, and building codes have to deal with the fact that they can't prevent all damage. At the present, we are not explicit about how much nonstructural damage is really acceptable, and an uninformed reading of the code would lead one to believe that the objective is to prevent almost all of it. That idealistic objective isn't really taken seriously and isn't appropriate, but what is?

The NEHRP Provisions document for new buildings (FEMA 222, 1991 edition) is even bolder: Section 8.2.4 states that "architectural components" (all 23 tabulated kinds, regardless of occupancy) "shall be designed for the design story drift of the structural resisting system...." except that ordinary partitions without fire separation or corridor functions in ordinary occupancies may be designed for half of that value. The related *Commentary* volume, sec. 8.2.4, interprets "designed for" to mean that "all architectural systems or components attached to or framed within the structural system must be capable of accommodating a story drift...without failure or should be separated from the structure...." The NEHRP Provisions have had an effect on the UBC and vice-versa over the years since ATC-3-06, but the primary embodiment of the NEHRP Provisions in model codes is their adoption into appendices to the BOCA and SBCCI model codes. Should we conclude that in the two-thirds of the country where seismic codes were never on the books until a year ago, virtually all built-in architectural nonstructural components are now being "designed for" the drifts calculated by structural engineers?

The reader should beware when terms such as "failure" are used without definition or when you can't find an illustration or a table explaining what constitutes a failure. In this same category of loose language is the concept of safety. Compare the following, imagining how a representative group of architects, engineers, contractors, and building officials from across the country would interpret these words when it comes to deciding exactly what is required on a specific project:

> [The purposes of these provisions] "are to minimize the hazard to life..." NEHRP Provisions 1.1
>
> "The purpose of this code is to provide minimum standards to safeguard life or limb, health, property and public welfare..." UBC 102
>
> "The SEAOC recommendations primarily are intended to safeguard against major failures and loss of life...[following sentence was added in 1988 edition but was not in earlier ones] The protection of life is reasonably provided, but not with complete assurance." SEAOC *Recommended Lateral Force Requirements And Commentary*
>
> "A building does not meet the life-safety objective of this handbook if, in an earthquake, the entire building collapses, portions of the building collapse, components of the building fail and fall, or exit and entry routes are blocked preventing the evacuation and rescue of the occupants." FEMA 178, *NEHRP Handbook for the Seismic Evaluation of Existing Buildings.*
>
> "If the design ground motion were to occur, there might be life-threatening damage in 1 to 2 percent of buildings designed in accordance with the *Provisions*. (In each building so damaged, on the average, about 1 percent of the occupants might be major casualties.)" NEHRP Commentary 1.4.1
>
> "When the structural failure of the lateral force-resisting system of nonrigid equipment would cause a life hazard...." UBC 2336 (a)
>
> "...the design of tanks and vessels containing sufficient quantities of highly toxic or explosive substances to be hazardous to the safety of the general public if released...." UBC 2336 (b)
>
> "These drift limits may be exceeded when it is demonstrated that greater drift can be tolerated by both structural elements and nonstructural elements that could affect life safety." UBC 2334 (h) 3
>
> "Drift limitations shall be established for structural or nonstructural elements whose failure would cause life hazards." UBC 2338 (a) 5

There has been a lot of talk about nonstructural components, and the codes would give the casual reader the impression that the problem is being rationally and comprehensively dealt with, but it's mostly just talk. Perhaps we should write a seismic code to meet a new type of dual level standard, the Philadelphia Standard: If a Philadelphia lawyer can't find a loophole in the provisions but if a Philadelphia engineer can still understand them, it's a well-written seismic code. (The intent is not to provoke engineers from Philadelphia but merely to use that city as an example of one of many areas of the US where seismicity is low-to-moderate and seismic codes are unfamiliar).

If nonstructural component damage is never a big problem, we shouldn't waste time trying to improve the situation. Some people think all nonstructural damage is trivial; some people find it difficult to accept even a very low level of acceptable damage because they're uncomfortable with any possibility of earthquake losses. How big a problem is nonstructural damage? This question can only be answered by analyzing the risks posed by the damage--the risk of casualties, the risk of property loss, and the risk of disruption of essential functions. There are various valid answers to these questions, depending on the circumstances of the building, but there are two answers that are definitely wrong:

Nonstructural damage is never a big problem.
Nonstructural damage is always a big problem.

Table 7-1: Summary of Issues In Performance Quantification Of Nonstructural Components

7.1 Prescriptive Versus Performance-Based Approaches: How should we choose between prescriptive and performance-based approaches?

7.2 Nonstructural Performance Parameters: How should the parameters of nonstructural earthquake performance be defined?

7.3 Parameters of Ground Motion and Building Motion: How should nonstructural performance be related to the motion of the ground and that of the building?

7.4 Communication of Performance Objectives: How should nonstructural performance objectives be communicated?

7.5 Roles Of The Construction and Design Industries: How should we identify the seismic protection measures for nonstructural components that require a change in construction industry practice, as compared to those that must be implemented by the design industry?

7.6 Strategy For Involving The Construction And Design Industries: How should we develop the strategy to involve the construction industry, the design industry, and other fields in achieving nonstructural performance objectives?

Issue 7.1: Prescriptive Versus Performance-Based Approaches

Issue Statement

How should we choose between prescriptive and performance-based approaches?

Background

"Prescriptive" can mean that the seismic loads (in the case of equipment and other nonstructural items that vulnerable to their own inertial forces) or deformations (in the case of components such as glazing) are prescribed or derived from simple formulas or tables that prescribe all the factors. The word's meaning can be extended to include the way these loads or deformations are analyzed. It can also be used to refer to specified details for resisting the loads or tolerating the deformations. In the nonstructural field, the term has usually included these actual construction details--the gage of bracing wires, standard drawings of details for typical items, etc.--and so it will be used in that sense here.

Alternatives

1. The goal should be to develop performance-based methods of design and analysis for all nonstructural components and to phase out the use of prescriptive details.

2. The goal should be to codify more and more prescriptive details until this type of repetitive solution is available for all nonstructural components.

3. Prescriptive solutions should be allowed for buildings with low ground shaking hazard and low occupancy risk factors; performance-based solutions should be required in all other cases.

4. Acceptable prescriptive solutions should be related to performance objectives. New prescriptive standards should be developed where feasible. Performance-based analysis should be more specifically defined than in present building codes. For many cases, both prescriptive and performance-based methods will be acceptable, and selection will depend on implementation aspects, e.g., how many different details would be required if the performance-based approach is used, whether an accurate analysis can actually be performed to support a performance-based approach, or how much extra construction cost or extra vulnerability is attributable to rule-of-thumb solutions rather than more customized and exact answers.

5. The way the design or specification will be implemented, or the way the purchase of a product will be made, must be taken into account: An engineer's expertise can be assumed for the case of pre-cast cladding, whereas most water heaters will not be installed with the involvement of an engineer. Components that wear out quickly and will be re-installed many times over the life of the building are more suitable for prescriptive approaches. Regardless of other factors (seismic shaking hazard, type of construction, type of nonstructural component), the reality is that almost the nonstructural risks of almost all small-scale residential buildings must be dealt

with prescriptively, while in the case of the hospital the performance-based approach can be carried through where considered necessary or desirable.

Recommendation

Alternatives 4 and 5.

Issue 7.2: Nonstructural Performance Parameters

Issue Statement

How should the parameters of nonstructural earthquake performance be defined?

Background

Analyses of the structural components of a building can use stress and deformation as parameters of performance, with graphs of how a frame, wall, or entire building will perform up through the elastic range, then will experience localized or minor inelastic deformation, and then how well-defined failures will occur (a brace buckling, an unreinforced masonry wall shattering, an entire building collapsing). A tall cabinet of computer equipment may have two well-defined points on its curve of performance: No damage, even as it rocks and almost overturns, and complete destruction as it reaches the point where it tips over. The graph of a window's performance relative to stress or deformation may show no significant damage up to a certain point, and then it shatters. Partitions, stucco, and similar planar features might have their performance tabulated in terms of cracks per square foot, though if property loss is the concern, past a certain point the entire surface will be coated with new finish material or the old material removed and new installed. Structural performance parameters are better thought-out and more neatly defined than in the case of nonstructural components.

The introductory discussion included some examples of how safety (life safety, life hazard, protection of life and limb, etc.) requires greater definition if performance-based criteria for nonstructural components are to make sense.

The introduction also distinguished nonstructual damage from the risks to life, property, and function. Damage might be taken as the one basic nonstructural performance parameter. Alternatively, damage may be considered a secondary parameter that is of value in defining three primary risk parameters: Damage may or not pose a serious risk in terms of safety (the chance of serious casualties), property (chance of incurring large repair or replacement cost), or function (chance of an essential function being disrupted).

Of these, at least property loss has an agreed upon unit of measurement: dollars (yen, marks, etc.). The scale, however, is not determined: Are there definable quantities, acceptable damage ratios, that could be used to produce standard property protection performance objectives? "Casualties" requires further definition--is it only death and the kind of injury that would typically send a person to the emergency room that is of concern? If ingress of firefighters and rescue personnel and egress of occupants is part of the definition of safety, the unit of measurement is in essence debris and other causes of blocked routes. People are expected to escape a fire by climbing through an opening that is only twenty inches wide and twenty-four high, located three feet eight inches above the floor (UBC sec. 1204 and other national codes, which applies to all sleeping rooms up to the fourth story). How does this compare with requirements for post-earthquake access? In the post-earthquake setting, should we tolerate access that is more difficult than this? The seismic scenario that there will be serious damage, serious access disruption, and that there will be people who need immediate rescue because of injury, fire, or hazardous material release, is probably much less likely than the scenario that a fire will require someone to evacuate the same building. Most buildings live out their lives in this country without experiencing a significant earthquake, but most buildings experience at least one small fire in their lifespan. On the other hand, since fire departments will have their hands full (and in some areas their hoses empty) after an earthquake, should post-earthquake ingress/egress be better than for typical fire requirements? Functional loss is perhaps the most difficult to define, and isn't even attempted in detail in any model code. (Special design manuals or codes, such as for Veterans Administration hospitals, are an exception). If the fire station has a light sheet metal garage door that could be easily broken out, is it OK to exempt it from drift-tolerance requirements? Does the hospital cafeteria have to be able to serve food? Is all of the piping above the basement emergency operations center "essential," since if there are leaks the water may work its way down and render the EOC useless?

The basic point of a performance-based approach is that the designer will be able to proceed along a path of trade-offs, consider alternative and innovative analysis and design methods, avoid needless prescriptive rules that don't apply to the actual case at hand, perhaps save construction cost or reduce some other negative impact, and still consistently arrive at the right destination. To do this, questions such as these need to be answered. Though the designer who uses prescriptive solutions faces such questions less frequently or not at all, the rationale underlying prescriptive requirements should also be based on a logical formulation of performance objectives.

How can performance parameters be made specific enough so that component behavior can be engineered to meet a statement of required performance?

Alternatives

1. Performance should be defined in terms of small, medium, and large earthquakes as in the SEAOC *Recommended Lateral Force Requirements and Commentary,* or as in the *NEHRP Provisions Commentary.* No further developments are required.

2. Three parameters should be used: life safety (risk of casualty); property loss (risk of damage that will incur repair or replacement cost); disruption (risk of functional loss). Future effort is needed to rationalize the units of quantification and to define definite levels for these risk parameters, relating them to a basic damage scale or set of descriptions.

3. Only damage should be defined, according to units of quantification and scales that need to be developed, something like a Modified Mercalli Intensity scale just for tabulated nonstructural components. The individual designer will then relate damage to performance as appropriate on a particular project.

Recommendation

Alternative 2.

Issue 7.3: Parameters of Ground Motion and Building Motion

Issue Statement

How should nonstructural performance be related to the motion of the ground and that of the building?

Background

Samuel Plimsoll, a member of Parliament, drafted the Merchant Shipping Act of 1875, which required cargo ship hulls to be marked (with what came to be known as the Plimsoll Mark) to indicate safe load levels. At a glance, it could be verified that a ship leaving Great Britain for New York during December was safely loaded by seeing that the WNA (Winter North Atlantic) line was visible above the water level. The law was so successful in preventing hull break-ups and capsizing that it became an international standard, and related scales and markings were devised for other kinds of ships such as passenger vessels and sailing ships. In the past few decades, the rating system was revised to take into account data on a new era of hull design that began to produce more stability than the historic rules of thumb would have indicated: The Plimsoll Mark thus contains an element of performance-based design.

Can we devise a seismic Plimsoll Mark? Can we elegantly define demand so that it directly relates to capacity, at the same time standardizing performance objectives and clearly communicating all of this to technical and non-technical audiences alike?

Presently, the same calculations that are used to analyze the structure's response in terms of deflections are supposed to be used to analyze nonstructural components subject to the imposed deformation problem. For equipment and items sensitive to the inertial problem, two methods of equivalent static lateral force analysis are provided in the code (UBC or NEHRP Provisions). One method produces the base shear and its distribution for the overall building, to be resisted by the structure. Another formula with different terms is used to calculate the inertial force generated by the acceleration effects on the component's mass. At various times, the UBC has included the same importance factor related to occupancy that is used for the structural design, at other times it has not. Why are the inertial load calculations for structural and nonstructural components non-parallel?

Consider an example typical of many buildings and nonstructural components in Zone 4. (Similar overall results pertain for NEHRP Map Area 7). The structure is designed to resist about 20% of its mass as a lateral force while the nonstructural component's criterion would be 30%, both levels using the same stress basis. Neither figure is the real expected acceleration, but rather a much lower figure. Damping, overstrength, redundancy, and ductility are relied upon in the case of the structure to allow it to successfully resist higher actual force levels. Some of these same characteristics but usually not all of them, and in differing ways, allow the nonstructural item and its anchorage to resist greater than design level forces. For example, ductility is ensured for a concrete column by numerous provisions regarding tie spacing, bar laps, etc. This detailing is assumed when the code writers artificially reduce the load. For nonstructural components, what are the ductility requirements? For pipes and conduit, the UBC imposes a dynamic analysis requirement, or a doubling of tabulated force coefficients, unless they are made of "ductile materials and connections." The *Commentary* to the *NEHRP Provisions* notes that for piping systems "made of ductile materials such as steel or copper can accommodate relative effects by inelastically conforming to the supports' conditions." (8.3.4) Regardless of whether the piping is constrained at one place where it passes through a wall but is flexible for a long run on the other side? In the case of the structure, the loads are mythical but are carefully related to detailed ductility requirements. The ductility of the reinforced concrete joint or member is obviously more than just a matter of whether a ductile material such as steel is present – if so all reinforced concrete would be ductile by definition. The precise configuration of the bars is of course crucial. But in the case of nonstructural components, we are simply told that if the material is metal, the system is ductile.

A typical four-drawer file cabinet with uniformly loaded drawers has a stability limit of about 0.3g, which is the same as the force factor if this cabinet were to be anchored. In other words, its performance looks fine when checked against the code force level, without any anchorage. Such file cabinets tip over frequently in earthquakes, including cases where the measured accelerations are only about 0.2 g. These anomalies are sometimes explained by pointing out that the code applies to the anchored object, not the unanchored one, and that typical steel hardware designed to elastically resist the 0.3 level would have performed reliably because of safety factors, ductility, etc. The engineer might check an existing building's elastic lateral capacity against the elastic demand requirement of current code as one way of beginning an evaluation. By contrast, checking nonstructural components' capacity, in particular their stability, against code levels gives deceiving results. The anchorage design produced by using the code coefficient may be adequately reliable, but considered as a way of explaining to the typical designer what to expect in an earthquake, this method is cloaked in a disguise rather than laying bare its assumptions.

"Transparent" is the popular but incorrect term in the earthquake engineering field at the moment. Transparent methods or procedures obviously can't be seen at all. What is meant is not that we should have invisible analysis and design methods but rather naked ones. Writing an earthquake engineering paper with "Nude Analysis" in the title would make most people picture an unclothed person on a psychiatrist's couch, which, while having the virtue of greatly increasing the readership of what is typically a very dry body of literature, has the drawback that it is quite misleading. Perhaps we should be content to avoid the use of "transparent" as in "transparent analysis method" unless the word refers to the way the method is presented, packaged, etc.

Alternatives

1. Ground motion and building performance are both adequately described by the Modified Mercalli Intensity Scale.

2. The force level should be calculated as in the UBC or NEHRP Provisions, in which one coefficient is calculated for the structure and a different one for the nonstructural component according to different formulas. Drift calculations provide a common denominator for the structural and nonstructural analysis.

3. Ground motion should be defined in the same engineering terms used for structural analysis, and nonstructural analysis should be in the same terms as for the structure. If an equivalent static lateral force analysis is used to calculate structural loading, derived from maps that contains information about spectral response, then these same types of values should be used for the nonstructural analysis. Vertical distributions of forces on the structure should be related to floor-specific nonstructural force levels. If a push-over analysis is used to analyze structural components, then the deformation-sensitive nonstructural components should be analyzed as part of the same analysis method. If present code formats do not allow for direct transferability (e.g., because factors of safety, damping, or other factors are different), a new analysis format should be devised to allow the structural and nonstructural analyses to be parallel.

4. For each category of nonstructural component (partitions, floor-mounted tall shelving, windows, etc.), five parameters should be quantified or indexed:

   a. Deformation-dependent damageability (sensitivity to damage induced by drift or other distortion of building geometry)
   b. Shaking-dependent damageability (related to story-level accelerations and considering frequency content, perhaps in terms of period bands as in Blume's Engineering Intensity Scale, which contains nine total bands grouped into three simplified ranges

      (The above 2 parameters would be connected via a common damage scale containing damage states. For all components, no damage would be at one end and complete destruction at the other, but the intermediate states would have to be specific to a category of components.)

   c. Life safety risk factor (based on the degree of hazard posed as the item reaches each damage state)
   d. Property risk factor (related to cost of repair or replacement, in terms of damage ratios)
   e. Functional risk factor (the consequence of a damage state on function of the component)

Recommendation

Alternatives 3 and 4.

Issue 7.4: Communication Of Performance Objectives

Issue Statement

How should nonstructural performance objectives be communicated?

Background

The Insurance Institute devised the 5 mile per hour crash as the criterion for automobile bumpers. Car buyers can picture a car rolling along in a parking lot--that's about 5 miles per hour--impacting their car's bumper, and the result being no damage. Building codes (Underwriters Labs Standard Specification 790) classify the fire retardancy of roofing materials with an easy-to-understand grading system: Class A, Class B, Class C, and Non-Rated. Photos in roofing product brochures easily communicate the fact that Class A roofing can withstand a big pile of kindling set on fire; Class B survives a small pile of burning kindling; Class C just manages to pass the test when kindling the size of a large postage stamp is put on it and set afire. (Non-Rated roofing *is* kindling.)

Now consider how well we manage to communicate the way code-conforming buildings will perform when exposed to earthquakes: "Your building's structure will withstand without collapse the earthquake ground motion that has a 90% probability of non-exceedence in a 50-year exposure period, except that there is a 1 to 2% chance your building will fall down for some quirky reason anyway." If it isn't clear or intuitively obvious why those numbers make sense, would you prefer the statement "over 50 years there is a 10% chance the earthquake will be worse than the building is designed to withstand"? If probabilities are confusing, does it make more sense when put this way: "The average time between earthquakes of this severity is 475 years (or 474 to be exact)"? (Why is it that one gets the feeling that if we used a number system founded on something other than base 10, we would be using other round numbers that correlate with different ground motion levels, but the auto bumpers and the roofing would still be designed to meet almost the same standards because their criteria are more directly tied to principles of physics and the facts of everyday life?)

Having done a good job of communicating the criteria for the motion of the ground, we then proceed to do an even better job delineating how the building will behave under those conditions. The code tells us (actually it's in the fine print of separately printed commentaries) that when that earthquake does occur, some damage will occur. How much damage? A good question deserves a good answer: The range of damage extends from a few cracks and a little mess on up a little further to irreparable destruction.

It's a little less clear than that as concerns the nonstructural components.

You can be sure that code provisions make the risk you face from nonstructural damage greater than that of a meteorite coming in the window and hitting you as you sit on the couch and less than that of playing jai alai with hand grenades, but that leaves a gray area in between. Ask five engineers to look at photos of an earthquake damaged building: Some windows broken, some of the ceiling fallen down, a few doors jammed shut, some of the veneer spalled off. Did the building meet the letter and/or spirit of the code's nonstructural performance objectives? You'll probably get six different answers.

If the intent is to communicate performance objectives to the public in addition to the design professionals and code officials, there is a big job ahead. Perhaps this will never be achieved, and perhaps the public doesn't want to really know about earthquake risks, any more than people want to know the fatality rate per passenger mile for airliners as compared to private aircraft or for automobiles prior to deciding what mode of transportation to take. Perhaps the public want the professionals to come up with a reasonable standard, communicate clearly what would be a success in meeting the standard and what would fail, and let the ordinary person go about his or her life without further bother.

"The public" is the term intentionally used here because it is much broader than "the owner." Engineers too often make statements about "the owner" deciding all issues of building safety, as if a return to the laissez-faire situation of factories in Manchester during the heyday of the Industrial Revolution were the ideal model, let alone considering the fact that today we sometimes have one sophisticated mega-corporation owner of a building and another sophisticated mega-corporation, the tenant, hiring its own engineers to do an earthquake engineering study as part of the leasing process. We can avoid political preconceptions or assumptions as to the final use of design codes or methods by merely referring to "the non-technical audience" "lay people," or "the public," whatever role they may have. That assumption is used here.

Can we devise definitions of performance objectives that make sense to the public? At a minimum, can we clearly communicate these objectives to the design professionals?

Alternatives

1. Commentary in design codes and standards or resource documents should do a much better job of informing the design professional about performance objectives. The performance-basis should be explicitly stated so that the designer can use this information intelligently. The definition should produce a very small amount of variation among the assessments of knowledgeable observers as to whether actual or hypothetical earthquake damage scenarios meet or fail the criteria. When we devise technically sound performance objectives, we should also consider how well these can be communicated to the public.

2. Building owners, political leaders and government administrators, and other members of the public ultimately should decide which performance objective(s) to achieve for specific buildings, so common sense definitions they can understand must be developed.

3. Commentary in the SEAOC *Recommended Lateral Forces and Commentary* and *NEHRP Provisions* Commentary volume are adequate.

Recommendation

Alternative 1.

Issue 7.5: Roles Of The Construction and Design Industries

Issue Statement

How should we identify the seismic protection measures for nonstructural components that require a change in construction industry practice, as compared to those that must be implemented by the design industry?

Background

"Design professionals" has a classy ring to it. "Design industry" sounds mercenary by comparison, which is an argument in its favor in this context. Instead of the best architects and engineers, we should consider the mediocre ones, and we can be sure that they are plentiful because mediocre buildings are so common. Or less critically, let's just recognize that the design professions have their burden of profitability to bear, limitations on how much expertise they have acquired or will be able to acquire, pressures from clients that only rarely involve seismic performance and often involve objectives that are in conflict with what is required to produce good seismic designs. Also, conceiving of a design industry and a construction industry properly places the two fields in the proper context: The two industries combine to make buildings, and the point of performance-based design is that the overall result, the whole building, should be put together so as to achieve an intended result.

Hazardous materials stored on shelves are a significant nonstructural hazard. The shelves are a manufactured product that in many cases the architect didn't even specify. The hazardous materials are products that are purchased and placed on the shelves continually. Confining our attention to the realms of the design industry and the construction industry perhaps restricts the scope too far. Safety professionals of the OSHA or health and safety type, whether in the private or government sector, need to be involved. Manufacturers of furnishings, appliances, and other nonstructural items aren't considered part of the construction industry but some of their products pose significant nonstructural risks or could help supply neat solutions to such risks.

Alternatives

1. The design professionals – structural, mechanical, and electrical engineers, and architects – can implement any needed changes by the way they design buildings.

2. The construction industry should have the predominant role, because many nonstructural components are products that are specified and installed, unlike structural components that are construction materials assembled according to structural designs.

3. Almost all improvements will come about only if the design and construction industries collaborate, including vendors and manufacturers of products and safety professionals outside the design field. The proper sphere or lead roles for each needs to be identified. A determined effort will be needed to involve disciplines other than structural engineering.

Recommendation

Alternative 3.

Issue 7.6: Strategy For Involving The Construction And Design Industries

Issue Statement

How should we develop the strategy to involve the construction industry, the design industry, and other fields in achieving nonstructural performance objectives?

Background

The Structural Engineers Association of California established the Applied Technology Council as a non-profit organization after the San Fernando earthquake in 1971, and most of its projects since then have been devoted to earthquake engineering. (Although part of the idea of establishing ATC was to enable engineers to be paid for the volunteer time they were spending in devising code provisions, researching earthquakes, etc. this aspect of the founding of ATC remains illusive. California structural engineers still give large amounts of time when it comes to the earthquake issue. Time totaling a half million dollars was donated for post-earthquake inspections after the Loma Prieta earthquake.) Structural engineers in other western states and in Massachusetts, New York, and elsewhere are also actively involved. Mechanical and electrical engineers, however, do not establish entire research organizations devoted to earthquakes or staff seismic code committees by the dozens. And in comparison with the structural engineers, have architects felt they have a responsibility to play a role in the cause for seismic safety? The answer is found right at the beginning of the Modified Mercalli Intensity scale: "I: Not felt except by a very few under especially favorable circumstances."

While engineers, sometimes reluctantly, school themselves throughout their careers to make sure they are up to date with standards of practice, and architects positively thrive on changes in design fashions, the construction industry reacts to change only when prodded by strong market or regulatory forces.

Part of the task of developing design guidelines and codes or standards is the underlying work of collecting and analyzing earthquake performance data. Reports on the Loma Prieta earthquake enumerate in some detail the performance of the several thousand unreinforced masonry buildings in the region, or high rise buildings, or wood frame dwellings. Comparable reports weren't produced to survey the damage to the basic nonstructural components. Unless nonstructural damage data collection improves, and more test data are obtained, our fundamental understanding will not improve.

The different parties involved respond to different forces. They are all needed to obtain better solutions to nonstructural damage. How can they be brought together?

Alternatives

1. The present approach of obtaining some involvement of mechanical engineers on the committees of structural engineers that are devising seismic provisions, or of allowing broad input into the review of proposed standards by model codes and standards organizations, should be followed.

2. Inadequate cross-disciplinary interaction is occurring. Code committees should be established with careful consideration for full inter-disciplinary participation. Conferences, research projects, test programs, or production of resource documents by teams of individuals and organizations representing the major fields--structural, mechanical, and electrical engineering, with specialties (e.g., fire protection, safety engineering); architecture; interior design; construction; product manufacturing.

3. Earthquake damage data collection and analysis needs to be improved. Related to this is the cataloging of test data on families of nonstructural components, and information produced by actual designs (costs, construction aspects, etc.) Only when these sources of information are improved and integrated can other advances be made.

Recommendation

Alternatives 2 and 3.

Acknowledgments

Although the format used here is styled after ATC-28/FEMA 237, *Seismic Rehabilitation of Buildings Issues Identification and Resolution,* which has the appearance of impersonal objectivity, in fact this paper takes advantage of the charter granted by Jack Moehle when he invited me to write this paper and to include in it "provocative" concepts. Ideas contributed by others have been included here but after being filtered in a subjective way, which will hopefully stimulate workshop discussion. Unlike the ATC-28 document, which underwent a consensus review process, this paper merely states my own views.

Along with review of the work of numerous people who have written on the subject over the past few decades, I would like to acknowledge the benefit of recent conversations on the subject of

this paper. The usual reverse-disclaimer applies: All errors, omissions, blunders, etc. are mine, and the following summaries are too brief to avoid being oversimplifications.

Eric Elsesser emphasized the importance of considering nonstructural performance in the context of structural response. When components fail in one building while the same ones do fine in another, subjected to the same ground motion, this must be accounted for. The logical starting point in the nonstructural design process is the analysis of the behavior of the structure and structural-nonstructural interaction. Nonstructural components must be designed to resist their building-specific context. Conversely, designing the structure to have appropriate response to limit nonstructural damage should be considered in the design process, rather than simply assuming that the structural system decisions are primary and then nonstructural component design follows.

Bill Holmes suggested that solutions to the nonstructural problem have to be rational, and as the guiding creative mind behind ATC-28 (Seismic Rehabilitation Issues) which is now leading into ATC-33 (Guidelines and Commentary for the Seismic Rehabilitation of Buildings), Holmes has produced good examples of this rationality in the way those projects are subjecting the general idea of performance objectives to close scrutiny. Performance objectives must be related carefully to specific analysis procedures. Solutions to the nonstructural problem have to be reasonable as well as rational--because it isn't always a big enough problem to worry about. We can analyze ground motion throughout the country and put a number on that likelihood; we can analyze structures and nonstructural components and, as with Veterans Administration hospitals for example, come up with very reliable solutions. But we have to be reasonable in deciding where to apply sophisticated nonstructural protection--or any nonstructural earthquake protection at all--especially considering that only some nonstructural components are major hazards in most buildings and that in areas of moderate or low seismicity, the nonstructural components will be replaced many times over on average before any significant earthquake motion occurs.

Mary Comerio raised the question of how much performance information from tests and past earthquakes is available. If it is not very extensive, shouldn't we be suggesting that a more systematic effort be mounted? Hundreds of thousands of buildings were shaken significantly in the 1989 Loma Prieta earthquake, but the published tabulations of nonstructural damage are fragmentary. Standards-development organizations should be more extensively involved in nonstructural seismic criteria: Are there standards for achieving various levels of performance of a component, or are standards typically calibrated to one performance level that becomes code-minimum without this performance being explicitly defined? Appropriate performance for a hospital is different than for most buildings, related to post-earthquake function: Can we develop standards that will indicate how to design the component for safety and also what is required to keep it functional? When nonstructural performance is important enough, it should not just be treated as a factor that is dependent upon the structure: Instead of choosing a moment frame, a stiffer structural system might be appropriate, aside from structural considerations, simply because of the beneficial effect on nonstructural components. The fact that the building should be a whole but is designed in pieces--the structural, architectural, mechanical, and electrical pieces--is a major problem.

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