CALIFORNIA INSTITUTE OF TECHNOLOGY

EARTHQUAKE ENGINEERING RESEARCH LABORATORY

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PROCEEDINGS OF THE

U.S.-Japan Workshop on Mitigation of Near-Field Earthquake Damage in Urban Areas

Workshop Organizers

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EXECUTIVE SUMMARY

The U.S.-Japan Workshop on Mitigation of Near-Field Earthquake Damage in Urban Areas was held in Honolulu, Hawaii on January 5-7, 1998. The goal of the Workshop was to develop a better understanding of the effects of near-field ground motions in urban regions, and identify needs and opportunities for joint U.S.-Japan research on mitigation of these effects. Twenty-one delegates and observers participated in the Workshop.

Both the Northridge and Hyogo-Ken Nanbu earthquakes were associated with fault rupture within heavily urbanized regions, and the effects of both earthquakes were especially severe within what is called the near-field, near-fault, or near-source region. Failures to modern engineered structures were observed within the near-field regions of both earthquakes and many researchers believe that at least some of these failures were attributable to near-field effects that were not adequately addressed in previous seismic design codes and guidelines. The U.S. and Japan are separately engaged in research on near-field ground motions and their effects on urban regions, and both countries believe they would benefit from a joint research effort in this area.

Important background knowledge on the theme of the Workshop was provided through oral presentations from the participants. These presentations are summarized in Appendix III of these Proceedings. Plenary Workshop discussions identified a number of promising areas for joint research. These were coalesced into three broad categories: 1) ground motion issues, 2) structural issues, and 3) observation versus theory. Working groups were formed for each of these categories and assigned the task of describing the most promising research areas and developing draft research plans for the highest priority topics.

Draft research plans were developed for the following high priority topics:

1. Enhancement of near-field ground motion simulation procedures,
2. Development of an improved engineering representation of near-field ground motions,
3. Characterization of near-field ground motion effects for improved design, and
4. Reconciling observations and theory.

Details of the draft research plans are contained in these Proceedings.

It is hoped that the insights, observations, conclusions, and recommendations expressed in these Proceedings will benefit all researchers desiring to undertake joint studies on the mitigation of near-field earthquake damage in urban areas. The participants in the Workshop have resolved to continue to work both individually and collectively toward understanding the nature of near-field ground motions and their effects on structures.

ACKNOWLEDGMENTS

The Organizers wish to acknowledge the financial support of the U.S. National Science Foundation and the Japan Society for the Promotion of Science. Special thanks is given to Professor H. Iemura, Secretary for the Japan side, who was heavily involved in the planning of the Workshop and to Professor T. Okada who graciously stepped in at the last minute as Co-Chair of the Workshop. The Organizers also express their sincere appreciation to Ms. Denise Okamoto and Mrs. Sharon Beckenbach for their invaluable assistance in handling meeting arrangements and in the preparation of these Proceedings.

TABLE OF CONTENTS

INTRODUCTION

Within the time span of only one year, both the US and Japan experienced costly, destructive earthquakes. The Northridge and Hyogo-ken Nanbu earthquakes had many features in common. Each was associated with fault rupture within heavily urbanized regions, and the effects of both earthquakes were especially severe within what is variously referred to as the near-field, near-fault, or near-source region.

The near-field region of an earthquake is considered to be the region within several kilometers of the extension to the ground surface of the fault rupture plane. Even for moderate magnitude earthquakes, near-field ground accelerations, velocities, and displacements, can be quite high especially toward the direction of propagation of fault rupture. Peak accelerations can exceed 1g, while peak velocities may exceed 1.5 m/sec, and peak displacements can exceed one meter.

It has also been observed that the character of the time history of ground motions recorded within the near-field region is qualitatively different from that observed for conventional far-field earthquake ground motions. Rather than resembling a broad-band random process, as in the case of far-field motions, near-field motions exhibit distinct lower-frequency pulses. These pulses can place very high demand on certain types of buildings and other structures.

Failures to modern engineered structures were observed within the near-field region in both Northridge and Kobe. Researchers believe that at least some of these failures may have been the result of near-field effects that were not adequately taken into account in previous seismic design guidelines. It is crucial that these near-field effects be identified and thoroughly understood, and that appropriate mitigation measures be found to deal with these special ground motions. Near-field ground motions will inevitably occur again in future urban earthquakes in both the US and Japan. Steps must be taken now to prepare for the next Northridge or Kobe type event.

Both the US and Japan are separately engaged in research on near-field earthquake motions and their effect on structural response. It is believed that great benefit will be derived by both countries if the lessons learned by each are shared, and a consensus reached on the best means to mitigate against this important hazard. It is this conviction that motivated holding of the US-Japan Workshop on Mitigation of Near-Field Earthquake Damage in Urban Areas. The Workshop brought together some of the most knowledgeable individuals in the subject area of the Workshop from both the US and Japan. A list of delegates and observers is provided in Appendix I.

WORKSHOP OBJECTIVES

The objectives of the Workshop were to:

1. Share important lessons learned from the Northridge and Hyogo-ken Nanbu earthquakes as regards near-field ground motions and their effects on structures,
2. Develop a consensus regarding the nature of near-field ground motions and their unique effects on various types of structures, and
3. Determine future needs and opportunities for joint US-Japan research regarding the mitigation of near-field earthquake damage in urban areas.

RELATIONSHIP TO US-JAPAN RESEARCH INITIATIVES

The Workshop was held shortly after approval of cooperative urban earthquake disaster mitigation research programs in both the US and Japan. It therefore provided a unique opportunity to discuss draft plans for research under these new programs. The US program is funded through the US National Science Foundation, and the Japanese program is funded through the Japan Ministry of Education, Science, Sports, and Culture.

The purpose of the US program is to foster, in cooperation with Japan, interdisciplinary research for mitigation of urban disasters by focusing on five high-priority areas. The focus areas are: (1) performance-based design and engineering, (2) integrated social science and related multi-disciplinary research, (3) advanced steel structures, (4) geotechnical engineering systems, and (5) advanced technologies. Most relevant to this Workshop are areas (1), (3), and (4). Details of the program can be found at the web site http://www.nsf.gov/pubs/1998/nsf9836/nsf9836.htm.

A proposal for the Cooperative Research Program in Japan was submitted by the Disaster Prevention Research Institute of Kyoto University to the Japan Ministry of Education, Science, Sports, and Culture, and was accepted in the 1998 fiscal-year national budget plan. It will have a major impact in the coming years. The program consists of fourteen specific projects under three major categories: (1) development of an advanced technology to protect the built environment and the population from near field earthquakes, (2) high performance infrastructure systems for destructive urban earthquakes, and (3) comparative study of urban earthquake disaster management. Details of the program can be found at the web site http://www.dpri.kyoto-u.ac.jp/default.j.html.

The joint programs will be coordinated by national committees in the US and Japan. These committees will: (1) provide technical guidance, (2) organize and schedule coordination activities, (3) facilitate exchange of data, information, and personnel, (4) assist in developing partnerships, and (5) facilitate the transfer and utilization of knowledge and technology resulting from the joint research.

WORKSHOP METHODOLOGY

The Workshop was organized into plenary presentation sessions, plenary discussion sessions, and Working Group sessions. The Workshop Program is contained in Appendix II.

Each Workshop delegate and observer was invited to give a brief oral presentation on the theme of the Workshop. These presentations provided a basis for subsequent discussions and deliberations. The oral presentations are summarized in Appendix III of these Proceedings.

SUMMARY OF PLENARY DISCUSSIONS

Plenary discussions focused on the unique features of near-field earthquakes and needed areas for research. The following promising joint research areas were identified:

1. Prediction of near-field ground motions considering source, path, basin, site, and nonlinear soil effects including an accurate forward prediction methodology for the near-field pulse,

2. Identification of types and sizes of earthquakes and regions where near-field ground motions are important for design,

3. Development of simplified ground motion representations for deterministic and probabilistic structural analysis,

4. Studies of the relationship between free-field ground motions and structural input motions considering both shallow and deep foundations,

5. Studies to more fully understand how different generic types of structures respond to various types of near-field ground motions,

6. Development of standards and guidelines for mitigation of structural damage from near-field ground motions with emphasis on the most important parameters for design,

7. Development of effective techniques for retrofitting older structures to resist near-field demand including active control, base isolation, and other promising new technologies,

8. Systematic examination of both the successes and failures of structures subjected to near-field ground motions in Northridge and Kobe, and

9. Studies to reconcile the differences between theory and observed damage with the goal of improving both design and analysis procedures.

WORKING GROUP ORGANIZATION AND CHARGE

Based on the findings of the plenary discussions of research issues, Workshop participants were organized into three Working Groups. These Working Groups were focused on the following general topics: Working Group I - Ground Motion Issues, Working Group II - Structural Issues, and Working Group III - Observation Versus Theory. Each Working Group was assigned a subset of the research issues identified in general discussions.

The charge to each Working Group was to:

1. Select three highly promising cooperative research topics,
2. Describe how each of these research topics might be addressed in a cooperative research program, and
3. Develop an illustrative draft research plan for at least one topic indicating possible research goals and objectives, research products, and a research methodology.

WORKING GROUP CONCLUSIONS AND RECOMMENDATIONS

Working Group I - Ground Motion Issues (K. Irikura and P. Somerville, Co-Chairs)

The overall objective of the ground motion prediction topics that follow is the development of methods for characterizing near-field ground motion for use in design and evaluation. The products of this work will be reliable procedures, having a sound theoretical and empirical basis, for the development of ground motions for use in practical design and evaluation. The three most promising topics are as follows:

Topic 1. Earthquake Source Characterization. This work has the goal of developing improved procedures for earthquake source characterization for use in the prediction of near-field strong ground motion of future earthquakes. The results of this work are needed in Topics 2 and 3.

Topic 2. Enhancement of Near Field Ground Motion Simulation Procedures. This work has the goal of developing improved procedures for simulating near-field ground motions that address the transition from deterministic to stochastic characteristics at a period of about 1 second, and making progress towards the goal of developing standardized ground motion simulation procedures. The results of this work are needed in Topic 3.

Topic 3. Development of an Improved Representation of Near-Field Ground Motions. This work has the goal of developing an improved representation of near-field ground motion for use in analysis and design, using time domain characteristics in conjunction with spectral characteristics.

It is proposed that work on these most promising topics be done over a three-year time interval, with work on Topic 1 being done first for use in Topic 2, and work on Topics 1 and 2 being used in Topic 3.

Research Topic 1: Earthquake Source Characterization for the Prediction of Near Field Ground Motion.

Variable slip rupture models have been developed for both US and Japanese crustal earthquakes. It is important that the data from each country be documented, analyzed, and made available for use by researchers in both countries. The object of this research would be to develop improved procedures for earthquake source characterization for use in the prediction of near-field strong ground motion of future earthquakes.

The research would consist of data gathering, analysis and documentation coordinated between US and Japan investigators.

The major products of the research would be:

1. A data base of variable slip rupture models of past crustal earthquakes
2. Statistical analysis of rupture models, including variability

3. Scaling relations of earthquake source parameters used to predict strong ground motions, including variability

4. A data base of rupture complexity aspects of crustal earthquakes, including earthquakes that have variable slip rupture models (1) and other earthquakes

5. A data base of geometrical characteristics of major active faults in Japan and California

This research could be completed within one year, then updated as additional information becomes available.

Research Topic 2: Enhancement of Near Field Ground Motion Simulation Procedures

Currently, different approaches are used in the simulation of near-field ground motion in the US and Japan. In order to develop enhanced procedures, and work toward standardized procedures, we need to jointly evaluate these procedures, and use the results of the evaluation as a basis for enhancing them. Collaboration will also provide the benefit of cost sharing.

The objectives of this research topic would be to enhance existing strong motion simulation procedures for simulating near-field ground motions, with special focus on developing improved procedures that address the transition from deterministic to stochastic characteristics at a period of about 1 second, with the goal of developing standardized ground motion simulation procedures.

The research methodology would be to:

1. Evaluate the adequacy of existing strong motion simulation procedures for simulating near-field ground motions.

2. Include methods being used to develop design ground motions in the US and Japan.

3. Select data set for the validation exercise: specify earthquakes, near-field recording stations, fault rupture models, and seismic velocity models. The selected events should include the Kobe, Northridge, Landers and Loma Prieta earthquakes.

4. Test the existing ground motion simulation methods against recorded data, and quantify modeling error.

5. Identify preferred simulation procedures.

6. Enhance the preferred procedures with improved earthquake source characterization and wave propagation computation techniques. The improved source characterization will be developed using information from Research Topic 1

above, together with improvements in methods for combining the short period and long period components of the hybrid broadband simulation procedure.

Improved wave propagation techniques, to be developed in this task, include improvements in representation of the effects of 2D and 3D geological structure, such as basin edges.

Coordination/planning meetings should be scheduled at the beginning of the project to coordinate the testing of ground motion simulation procedures. Annual working meetings should be held to coordinate the development of enhancements in procedures for simulating near-field ground motions.

The major product of this research would be identification of the ground motion simulation methods that are most effective for representing near-field ground motions, and enhancement of those methods.

This work would span a three year time frame. The work could begin at the start of the project, and incorporate information on source characterization from Research Topic 1 after the first year.

Research Topic 3: Development of an Improved Engineering Representation of Near-Field Ground Motions

Near-field ground motion characteristics are the same in Japan as in the US. It is important to take advantage of this fact by combining the data sets from both countries, and developing a unified characterization of near-field ground motions for use in design and analysis in the US and Japan.

The objective of this research would be to develop an improved representation of near-field ground motion for use in analysis and design.

The basic approach to the research would be as follows:

1. Assemble a large set of near-field ground motion time histories using both recorded time histories and simulated time histories that: (1) represent the range of expected behavior of near-field ground motions, (2) span ranges of conventional parameters including magnitude, closest distance, site conditions, and (3) span ranges of additional parameters including rise time, azimuth, hypo-central distance.

2. Identify damaging characteristics of near field ground motions from nonlinear dynamic structural analyses using the large set of ground motion time histories and identify of potentially vulnerable building types.

3. Develop an improved parameterization of near-field design ground motions based on parameterization on damaging characteristics found in Step 2, which may include: response spectrum, Fourier spectrum, period and amplitude of the pulse, and energy and power input of the pulse.

4. Develop a near-field ground motion prediction model and use this model to predict an improved ground motion parameter set (Step 3) from expanded source parameters (Step 1).

5. Develop a near-field pulse generation algorithm and generate 3-component time histories that embody the improved ground motion parameter set (Step 3) as predicted by the model (Step 4) from expanded source parameters (Step 1).

6. Validate the near-field ground motion model and confirm that the response of structures to the ground motion pulses for specified combinations of expanded source parameters (Step 5) is compatible with that obtained from recorded and simulated time histories having similar combinations of source parameters (Step 1, 2).

A coordination /planning meeting should be held at the beginning of the project to provide an interface between US and Japan investigators, and between engineers and strong motion seismologists. Annual working meetings should be held to discuss results.

During the first year, an improved ground motion parameterization would be developed while structural engineers perform generic analyses to identify potentially vulnerable building types. During the second year, the near-field ground motion model based on the improved parameterization would be developed using preliminary ground motion simulation results from Research Topic 2, while structural engineers analyze vulnerable building types. During the third year, the characterization of near-field ground motions using pulses would be developed for use in testing code applications by structural engineers.

The primary product of this research would be an improved representation of near-field ground motions for use in analysis and design, consisting of an improved set of ground motion parameters, quantification of the ground motion parameters as a function of the predictive parameters (magnitude, distance, site conditions, and rupture directivity conditions), and a computer algorithm that generates near-field pulses that represent the ground motions for specified predictive parameters.

Example Draft Research Plan: Enhancement of Near-Field Ground Motion Simulation Procedures

Near-field ground motion that caused heavy damage during the 1994 Northridge earthquake and the 1995 Kobe earthquake are characterized by one or two distinctive large pulses with relatively short duration. Such large pulses are generated by forward rupture directivity effects in the fault-normal component which is caused by the coherent summation of ground motions from extended fault planes. The durations and amplitudes of the pulses are related to geometrical relations between fault plane and site, rupture velocity, slip heterogeneity, and so on. Near-field ground motions are further amplified by the basin edge effect. The basin edge effect originates from constructive interference between seismic waves that diffracted at the basin edge and proceeded into the basin and direct S

waves vertically propagating through the sediments from the basin bottom. The basin edge effect caused damage concentration in narrow zones running parallel to the causative faults during the 1995 Kobe earthquake. Ground motions at soft soil sites were reduced because of nonlinear behavior of soft soil layers for strong ground motion.

Such destructive motion in the near-field region cannot be represented by the response spectrum alone considering phase characteristics in a stochastic process. There is a need to enhance computational methods for near-field motions based on kinematic source models and realistic geological structure models.

Current methods for computing near-field ground motions may be organized into three categories: (1) theoretical methods, (2) semi-empirical methods, and (3) hybrid methods. The theoretical methods may be further subdivided according to the use of extended fault models with 1-D structure (1-D model), extended fault models with 2-D structure (2-D models), or extended fault models with 3-D structure (3-D models).

The 1-D model approach includes the methods of Bouchon (DWNM) and Olson and Apsel (DWFEM). Both of these methods have been used for source inversion from strong ground motion records. The advantages of the 1-D model approach are: ease of modeling, relatively broad frequency range (up to about 5 Hz), stable result, and less consumption of computer memory. The disadvantage of this approach is that it is feasible to compute the forward directivity effect but not the basin edge effect.

An important 3-D model approach is the finite difference method (FDM) based on the work of Graves and Pitarka and Irikura. The advantage of this approach is that it is very powerful as long as detailed geological structure models and source model are available. The disadvantages of the approach are that it is difficult to construct the structure model, computation is time consuming, and there are limitations on the frequency range. Other approaches include those of Bielak (FEM), Sanchez-Sesma and Fujiwara (BEM), and Helmberger (GR). These theoretical approaches are very useful for frequencies less than 1 Hz but, with the exception of the GR method, are very difficult to apply for frequencies greater than 1 Hz.

The semi-empirical method is very powerful as long as appropriate small event records are available from target source areas. This has been shown by the work of Hartzell, Hadley and Helmberger, Boatwright, and Irikura. The primary disadvantage of this approach is that appropriate records are often not available

To overcome disadvantages for theoretical and empirical methods, various combination methods have been proposed. These include the hybrid approaches of Somerville, et al. (empirical source time function combined with theoretical Green's functions), Heaton et al.(1995) (1-D model for low frequency and actual data from other earthquakes for high frequencies, and Kamae Pitarka and Irikura (BSSA 1998) (combination of 3-D modeling for low frequencies with stochastic simulations for high frequencies, and empirical Green's function simulation method). Other approaches have been employed by Midorikawa and Kobayashi (1979).

The following work plan has the objective of validating the methods described above using recorded data from earthquakes such as the 1994 Northridge and 1995 Kobe earthquakes to identify their ranges of applicability and limitations. The work would be conducted over a three year period.

1. Evaluate the adequacy of existing strong motion simulation procedures for simulating near-field ground motions. Include methods described above, which are being used to develop design ground motions in the US and Japan.

2. Select a data set for the validation exercise. Specify earthquakes, near-field recording stations, fault rupture models, and seismic velocity models. The selected events should include the Kobe, Northridge and Loma Prieta earthquakes.

3. Test the existing ground motion simulation methods against recorded data, and quantify modeling error.

4. Identify preferred simulation procedures.

5. Enhance the preferred procedures with improved earthquake source characterization and wave propagation computation techniques. The improved source characterization will be developed using information from Research Topic 1, together with improvements in methods for combining the short period and long period components of the hybrid broadband simulation procedure. Improved wave propagation techniques, to be developed in this task, include improvements in the representation and computation of the effects of 2D and 3D geological structure, such as basin edges.

Example Draft Research Plan: Development of an Improved Engineering Representation of Near-Field Ground Motions

The propagation of fault rupture toward a site at a velocity close to the shear wave velocity causes most of the seismic energy from the rupture to arrive in a single large long period pulse of motion that occurs at the beginning of the record. This pulse of motion, sometimes referred to as "fling," represents the cumulative effect of almost all of the seismic radiation from the fault. The radiation pattern of the shear dislocation on the fault causes this large pulse of motion to be oriented in the direction perpendicular to the fault strike, causing the strike-normal peak velocity to be larger than the strike-parallel peak velocity.

The effect of forward rupture directivity on the response spectrum is to increase the level of the response spectrum of the horizontal component normal to the fault strike at periods longer than 0.5 seconds. This causes the peak response spectral acceleration of the strike-normal component to shift to longer periods, for example from 0.25 seconds to as much as 0.75 seconds. Near field effects cannot be adequately described by uniform scaling of a fixed response spectral shape; instead the shape of the spectrum becomes richer in long periods as the level of the spectrum increases.

Although the response spectrum provides the basis for the specification of design ground motions in all current design guidelines and code provisions, there is a growing recognition that the response spectrum alone does not provide an adequate characterization of near-field ground motions. This is because near field ground motions are characterized by a relatively simple long period pulse of strong motion having relatively brief duration, rather than by a stochastic process having relatively long duration that characterizes more distant ground motion. Unlike the case for more distant ground motion, the resonance phenomenon that the response spectrum is designed to represent has no time to build up when the input is a near-field pulse. The response spectrum is thus not capable of adequately describing the seismic demands presented by a near-field pulse.

Nonlinear structural response analyses, including the use of time history inputs, will be required to meet the goals of performance based design. It is well known that different ground motion time histories that all match the same response spectrum produce variations in the response of a structure subjected to nonlinear time history analysis. When the input time history is a near-field pulse, this effect is accentuated to the point where small modifications of a near-field time history that have no significant effect on the response spectrum can have a major effect on the response of a structure when subjected to nonlinear time history analysis. This demonstrates that the current standard of practice does not provide a reliable basis for providing near-field ground motion time histories that are specified solely on the basis of a design response spectrum.

The objective of the work plan that follows is to develop an improved characterization of near-field ground motions that supplements the response spectrum with time domain parameters such as the duration and amplitude of the near-field pulse, and the energy and power input that it presents. This approach requires the interaction of strong motion seismologists and structural engineers. The work would be conducted over a three year period.

1. Assemble a large set of near-field ground motion time histories that represent the range of expected behavior of near-field ground motions

   The ground motion time histories should represent not only ranges of parameters that are currently used in predicting strong ground motions, such as magnitude, distance from the earthquake source, and geologic site conditions, but also ranges of other parameters that are known to influence near-field ground motion characteristics. These include the distance and azimuth from fault strike between the point of rupture initiation and the site, and the rise time (duration of slip on the fault). To augment the data set of near-field strong motion recordings, especially for larger magnitudes and closer distances than are available in the recorded strong motion data set, and to provide estimates of the effect of source parameters on near-field ground motions, we need to use broadband simulations of near-field ground motion time histories.

2. Identify damaging characteristics of near field ground motions

   By performing a large number of nonlinear dynamic structural analyses using the large set of ground motion time histories, identify the time histories that are most damaging to structures, and identify the characteristics of the near-field pulse that are most damaging to structures.

3. Develop an improved parameterization of near-field design ground motions

   Use the ground motion characteristics that are most damaging to structures to develop an improved parameterization of near-field ground motion. The ground motion parameters may include time domain parameters that describe the near-field pulse, such as its period and amplitude, in conjunction with parameters describing energy or power input, as well as parameters that describe the spectral content such as Fourier amplitude or response spectral amplitude. Confirm that structural response is sensitive to variations in these parameters.

4. Develop a near-field ground motion prediction model

   Develop a model for predicting the ground motion parameter values of the improved parameterization from earthquake source parameters. The earthquake source parameters used to predict the ground motion parameter values, beside including the conventional ones of magnitude, distance, and site conditions, should also include parameters that are known to influence near-field ground motion characteristics. These include the distance and azimuth from fault strike between the point of rupture initiation and the site, and the rise time (duration of slip on the fault).

5. Develop a near field pulse generation algorithm

   Develop an algorithm which allows the ground motion parameters to be represented in a suite of three pulses (for the strike-normal, strike-parallel and vertical components of motion) which satisfy the pulse duration, amplitude, energy and power input, and Fourier or response spectral ordinates specified by the model.

6. Validate the near-field ground motion model

   Test the adequacy of the ground motion model by confirming that the response of structures to the ground motions for specified combinations of magnitude, distance and site conditions is compatible with that obtained from available strong motion recordings having similar values of magnitude, distance and site conditions.

Working Group II - Structural Issues (H. Iemura and H. Krawinkler, Co-Chairs)

It is generally accepted that near-field demands are greater than implied in current codes and likely exceed expected capacities. Therefore, it is necessary to predict demands in order to make sure that capacities exceed demands. In some cases, large demands may only be in localized areas, but it may not be possible to ignore even these local high demands. In order to make capacities exceed demands, it is necessary to either decrease demands, or increase capacities. But what is the cost? Also, consideration must be given to higher performance levels (e.g. damage control). In Japan, the Code is a minimum, therefore, consideration of near-field effect is considered a special issue.

High-rise and conventional buildings (4-5 stories) are generally designed differently and may perform differently when subjected to near-field ground motions. In Japan, the design spectrum (which is different from ground motion spectrum) will be defined at bedrock, and other effects are considered as modifications. However, near-field ground motions result primarily from source effects that also influence rock motions. There seems to be confusion about this among some earthquake engineers.

There is a need to understand the real performance of buildings and other structures, and to incorporate this understanding into codes. But this raises the issue of how to verify performance. Should this be done using ground motion time histories or a design spectrum? How should judgment be exercised in developing ground motion for performance evaluation? Research is needed to establish the process for "engineering judgment". The characterization of uncertainty in response of structures to near-field motions is also important. Once uncertainties have been characterized, it is important to find ways to minimize these uncertainties.

Knowledge gained regarding near-field effects must be translated into design criteria. This requires an understanding of the difference in near-field response as compared to standard ground motion response. It also requires methods to characterize these differences and account for them in the design processes. A separate issue is how to take care of near-field effects in existing structures. Beside conventional strengthening approaches, consideration needs to be given to both passive and active control solutions.

The following research is believed by the Working Group to be of high priority for understanding the response of structural systems subjected to near-field ground motions:

Research Topic 1: Characterization of Near-Field Ground Motion Effects for Improved Design

The objectives of this research would be to:

1. Improve understanding and characterization (quantification) of unique features of near-field ground motion effects,

2. Improve design for life (collapse) safety performance, and

3. Improve design for functional performance.

The primary product of this research would be a comprehensive report; including recommendations on incorporation of near-field ground motion effects in seismic design.

The following research methodology is recommended:

1. Form research team (ground motion expert and structural engineer each from US and Japan)
2. Form advisory group (practicing engineers, other researchers, code writers)
3. Hold coordination/planning meeting in Japan
4. Perform analytical studies on generic structures
5. Perform analytical studies on "real" structures
6. Compare results to observed damage (interact with Working Group III)
7. Establish performance-based design format for near-field ground motion effects

The time period for this research would be three years.

Research Topic 2: Characterization of Uncertainties in Response of Structures to Near-Field Ground Motions

The objectives of this research would be to:

1. Improve reliability, and
2. Understand sources and quantify magnitude of uncertainties, and develop means to minimize uncertainties in demands and capacities.

The primary product of this research would be a consensus report.

The following research methodology is recommended:

1. Form team of ground motion and structures experts,
2. Use Working Group approach (US and Japanese Working Group members),
3. Perform research (ground motion & response evaluation), and
4. Hold three workshops (beginning, mid-way, end).

The time period for this research would be three years.

Research Topic 3: Seismic Retrofit Procedures for Near-Field Ground Motion Effects

The objectives of this research would be to:

1. Develop methodologies for seismic diagnosis of existing structures
2. Identify the need for retrofitting of different types of structures, and
3. Identify and develop retrofit approaches that are particularly effective for improving performance under near-field ground motions.

The principal research product would be a report; including guidelines for effective retrofit procedures.

The research methodology would consist of coordinated analytical studies of many structures and structural types. The time period for the research would be three years

Research Topic 4: Feasibility of Structural Control for Near-Field Ground Motion Effects

The Northridge and Kobe earthquakes have revealed that near-field ground motions have very damaging effects on structures. With conventional earthquake resistant design techniques it is difficult to maintain function of structures under near-field ground motions. This study aims to develop design methodologies to achieve high performance of structures by means of structural control techniques.

The objective of the research would be to improve performance of structures against near-field ground motions using structural control techniques. The principal product of the research would be a report; including design methodologies incorporating structural control.

The applicability of base isolation devices, energy absorbing devices, and active and hybrid control devices will be examined through numerical simulations and experiments. The schedule for this research could be as follows:

Year 1: Investigation of feasible types of structural control techniques

Year 2: Numerical simulations of structures with control devices

Year 3: Development of design methodologies

Example Draft Research Plan: Characterization of Near-Field Ground Motion Effects for Improved Design

This project would address the following issues:

1. What are the differences between near -field ground motion response and standard ground motion response (considering 3D input)?
2. How can these differences be characterized?
3. How can these differences be accounted for in the design process?

4. How can near-field ground motion effects be placed within the context of a performance-based design approach that addresses different performance levels?

The research needed to address these issues should be performed by a team of researchers from the US and Japan. The work will need continuous interaction between engineering researchers who would perform structural evaluations, and earth scientists who would provide the information on the range of characteristics of the ground motions that have to be considered. The result of the engineering studies would be a comprehensive assessment of the force and deformation demands imposed by near-field ground motions on different types of structures (frame and wall structures). Studies should be performed on elastic and inelastic structural systems, utilizing "generic" structures and "real" structures. "Generic" implies that structural properties (e.g., period, base shear strength, and distribution of strength over the height) will be varied in a systematic manner with comprehensive parameter variations. This part of the research is needed in order to accomplish an assessment of the effects of structural parameters on seismic demands imposed by near-field ground motions. Near-field ground motion parameters that significantly affect the seismic demands would be identified and sensitivity studies will be performed to evaluate the effect of these parameters on seismic response. Considering that great variations in the characteristics of near-field ground motions have to be expected, an assessment of the uncertainties in demands would form an essential part of this study. The results would be evaluated in the context of design procedures presently employed in the US and Japan.

An assessment of the demands imposed on "real" structures is essential to calibrate/verify the conclusions drawn from the analytical studies with generic structures. Such a calibration needs to encompass two types of real structures. Preference should be given to existing structures that have experienced near-field ground motions in recent earthquakes. For a comprehensive calibration it may be necessary to complement the small set of qualifying structures with a set of code designed structures that simulate realistic conditions. Most of this work is proposed in a companion project under Working Group III. If that project receives funding, duplication will need to be avoided and close collaboration implemented.

An essential part of this research would be an effort to develop and formulate design recommendations in a performance-based design context that pays close attention to parallel efforts going on in this area in both the US and Japan. In this effort, the emphasis would be on low performance levels (life safety, collapse prevention), but attention would also be given to behavior at higher performance levels (operation, damage control). This implies that near-field ground motions with shorter return periods will also have to be generated and evaluated.

The distinguishing features of this research project are close collaboration between earth scientists and structural engineers, and between participants of the US and Japan. The main reasons for the latter are:

1. Expansion of data base available to researchers,

2. Availability and sharing of work, resources, and results from both countries,
3. Expansion of knowledge base available for research,
4. Providing different perspective on issues of common interest,
5. Learning about differences in design philosophy, procedures, and practices, and
6. Harmonization of design approaches in a performance based format.

The following process is envisioned to facilitate collaboration for maximum mutual benefit.

Coordination/Planning. At the beginning of the project a coordination/planning meeting would be held in Japan (travel for US participants to be included in project budget). If feasible, this meeting would be scheduled together with meetings of related projects for global coordination. The state-of-knowledge on pertinent subjects would be reviewed (work on several aspects of the proposed research is already in progress in the US and Japan, and duplication must be avoided), important gaps in knowledge would be identified, a detailed year 1 work plan would be established, and well-defined work assignments would be made for US and Japanese earth science and engineering participants. Research work would be done in independent but coordinated projects.

Advisory Committee. An Advisory Committee would be established to provide input to all aspects of the work. This committee should include practicing engineers, code writers, and researchers working on related subjects.

Research Team. Members of the joint research team would communicate regularly and post progress and research results on a web site. A mechanism for exchange of personnel (to the extent feasible within budget constraints) would be established and implemented. Progress would be reviewed at annual working meetings of the Principal Investigators of both countries, with input provided by the Advisory Committee. The working meetings would be scheduled to coincide with completion of milestones that may require a re-assessment of future work and/or coordination of work with, and information transfer to, related projects. Evaluation of work progress needs to emphasize the benefits to present and future design practices in both countries. At the working meetings plans and schedules should be developed for dissemination of the research results to the user communities in both countries, utilizing conventional mechanisms (seminars, workshops) as well as internet based information transfer and learning modules.

Working Group III - Observation and Theory (S. Otani and M. Sozen Co-Chairs)

As early as the 1966 Parkfield earthquake, near-field effects were observed in recorded strong motion accelerograms. In the recent Northridge and Kobe earthquakes, large velocity pulses were recorded and have been tied to the near-field effects. Using these ground motion records to study the response of idealized structures, it has been found that this type of ground motion can cause significant structural damage. To this point, no

instrumented buildings or bridges that were subjected to near-field motion have been studied to verify the findings of these analytical studies. Recorded building responses that were not available immediately after the earthquakes are now becoming accessible in the US and Japan, and provide an excellent opportunity for cooperative research to evaluate current analytical modeling techniques and investigate the influence of near-field ground motion on buildings and bridges. Only one research topic was developed by this Working Group.

Example Draft Research Plan: Reconciling Observations and Theory

The proposed research would have two primary objectives:

1. Evaluate the potential of near-field ground motions to cause extensive damage in the urban environment and the need to include near-field effects in design procedures by using field evidence, and

2. Test the reliability of current analytical tools to reproduce the response of buildings and bridges subjected to near-field strong ground motion.

Analytical studies of framed structures subjected to near-field motions indicate that distributions of story shears are not consistent with current design philosophies. Damage in the structures was related to the ratio of the fundamental period of the structure and period of the velocity pulse. The results from these studies are sensitive to the choice of analytical model used to represent the structure and the characteristics of the ground-motion pulse. However, neither of these conclusions has been verified using measured structural response to recorded ground motions. The influence of near-field motion on actual structures may be over-estimated because of the inherent strength and stiffness of non-structural elements that have not been considered in these analyses. In addition, the traveling wave effect in a building may not be well represented by the typical lumped-mass structural model.

The near-field ground motions measured in Northridge and Kobe were quite different. The Northridge event included a single pulse, while the recorded motions in Kobe exhibited multiple pulses. Different response is expected in a structure subjected to these two types of ground motion. Development of analytical tools that are capable to reproducing observed structural response in both settings will lead to reliable tools for developing new design procedures.

Analysis and design procedures as well as typical structural configurations are different in the US and Japan. Observed damage after the two earthquakes were similar in some respects, but different in others. These differences could be due to the different nature of the ground motions or because of the differences in the design philosophies and analysis procedures. By fostering this cooperative research program, the best concepts from each country can be identified and used to improve structural performance in both countries. This opportunity is available for both reinforced concrete and steel buildings and bridge structures.

Candidate structures in both countries would be identified. These structures would be located in regions with the strongest ground motion. The structures must have strong-motion instruments at the base and distributed throughout the structure. It would be desirable, but not necessary, to have recorded free-field motions near the structure. Identifying damaged structures would be the first priority; however, comparative studies with instrumented undamaged structures in the same area would also provide valuable information. The following instrumented structures have been identified as possible candidates: steel reinforced concrete buildings in Kobe which sustained minor damage, damaged steel buildings in Northridge, the Higashi-Kobe Bridge in Higashi-Nada Ward, and a building on Port Island which also included a deep ground-motion instrument.

Analytical models of the selected structures would be formulated. Blind tests would be conducted, where the researchers are given only the recorded base motion. Calculated responses would then be compared with the recorded motions to evaluate the reliability of current modeling procedures. Analytical models would then be adjusted to reflect the measured response of the structures.

Once the analytical models have been verified, the near-field effects can be evaluated by subjecting the structures to different ground motions. In particular, using recorded ground motions from both countries would provide a means of relating expected structural damage to the near-field ground motions. The results of these studies will also provide a means of identifying the best design practices in both countries and appropriate procedures for incorporating near-field motions into the design process. The results of these studies will also be useful for developing performance-based design procedures in both countries, because reliable analytical tools are required.

In addition to evaluating current procedures for calculating structural response, the instrumented buildings considered in this investigation will also provide a means of verifying the procedures developed to calculate near-field ground-motion records at specific locations.

Following the completion of this research, it is considered desirable to test a representative building on the earthquake simulator that is currently planned by the Science and Technology Agency in Japan. This facility will provide a unique opportunity to text structures at nearly full scale subjected to large-amplitude ground motions.

APPENDIX I - LIST OF PARTICIPANTS

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APPENDIX II - WORKSHOP PROGRAM

Day 1 (January 5, 1998)

Time	Activity	Topic	Speaker
0800		Call to Order and Opening Remarks	
0830	*Session I* *Chair: T. Okada and W. Iwan*	Opening Remarks	T. Okada
		Implications of Near-Field Ground Motions for Structural Response	W. Iwan
		Strong Ground Motion Prediction for Active Faults with High Earthquake Potential	K. Irikura
		Development of and Improved Parameterization of Near-Field Ground Motions	P. Somerville
		Modeling of Phase Characteristic of Design Earthquake Motion	T. Sato
		Level 2 Ground Motions for Civil Engineering Structures	T. Ohmachi
		Selection of Near Field Scenario Earthquake for Zonation	H. Kagami
1015	Break		
1045	*Session II* *Chair: H. Iemura and D. Foutch*	Damage Statistics of Reinforced Concrete Buildings from Past Earthquakes	S. Otani
		Effects of Near-Field Ground Motion on Long Period Building Structures	H. Krawinkler
		Conventional Reinforced Concrete Frames and "Near-Field" Motions	M. Sozen
		Influence of Vertical Ground Motion on the Response of Precast Parking Garages	S. Wood
1200	Lunch		
1300	*Session III* *Chair: S. Otani and M. Sozen*	Ductility and Strength Demand for Near Field Earthquake Ground Motion	H. Iemura
		Near-Field Ground Motions and Hysteresis Type on the Collapse-Potential and Response of Buildings during Earthquakes	D. Foutch
		Comparative Studies of Near Field Earthquake Damage in Urban Areas	M. Nakashima
		The Effect of Near-Source Ground Motion on Long-Period Base-Isolated Structures	M. Halling
1400	Break		
1430	*Session IV* *Chair: M. Nakashima and H. Krawinkler*	Developments of Early Earthquake Loss Estimation Systems	F. Yamazaki
		Development of Smart Structural Systems	H. Hiraishi
		Development of Performance-Based Structural Design in Japan	M. Midorikawa
		Fundamental Research for the Mitigation of Earthquake Disaster–NCREE Research Progress	C.H. Loh
		Strength-Reduction Factors for Structures with Triangular Steel Plate Energy Dissipation Device	H. T. Chen

1530		Overview of Japan and U.S. programs	S. Otani M. Sozen
1600	Adjourn		
1730	Workshop Dinner		

Day 2 (January 6, 1998)

Time	Activity	Topic	Speaker
0800		*General Discussion* *Unique Features of Near-Field Earthquakes* *Important Technical Issues*	
1000	Break		
1030		*Working Group Assignments/Meetings* *Develop Task Statements*	
1200	Lunch		
1300		*Presentation and Discussion of Task Statements*	
1400	Break		
1430		*Working Group Meetings*	
1630	Informal Dinner		

Day 3 (January 7, 1998)

Time	Activity	Topic	Speaker
0800		*Individual Writing Assignments*	
0930	Break		
1000		*General discussion of recommendations and conclusions*	
1200	Lunch		
1300		*Complete writing assignments*	

APPENDIX III - SUMMARY OF WORKSHOP PRESENTATIONS

(In order of presentation)

Mitigation of Near-Field Earthquake Damage in Urban Area

Tsuneo Okada
Shibaura Institute of Technology

Since Professor Toki, Japanese coordinator, could not come to the seminar due to the fact that he was elected as Dean of the Faculty of Engineering at Kyoto University, I am making a short address at the opening of the U.S.-Japan seminar for him.

In order to mitigate earthquake damage, it is very essential to keep continuing the fundamental research and to accumulate the data and knowledge to improve the seismic design and practice. However, for about 10 years before Northridge and Kobe, it has not been well recognized except by research communities. Because, even if the earthquake damage had been repeated in the world, since the damage both in the U.S. and Japan seemed not so serious, it is misunderstood that the earthquake damage mitigation could be achieved by the application of existing knowledge and technologies without fundamental research. Both events in Northridge and Kobe changed the situation much. After Northridge and Kobe, the word of "earthquake disaster mitigation" has become one of the most popular words in both countries. Governments in both countries have also recognized the importance to promote the fundamental research works on earthquake engineering. One of the most important issues is the Clinton-Hashimoto Common Agenda. Based upon the Common Agenda, responsible agencies in both countries are encouraging research communities to establish U.S.-Japan cooperative research projects. Since 1995, several U.S.-Japan joint workshops have been held to discuss the feasibility of joint projects; for example in Maui, December, 1995, in Tokyo, February, 1997, and others. In both workshops, the high priority research topics for the U.S.-Japan joint projects were discussed in general. However, the detail discussion about specified topics have not been well done due to the limitation of the time. The scope of this workshop is 1) to identify important research issues learned from Northridge and Kobe, and 2) to discuss possible U.S.-Japan cooperation in the field of near field ground motion and performance-based structural design. However, I do hope we focus our discussion on the second objective and deepen the discussion, because the size of the workshop is quite proper to do so.

Implications of Near-Field Ground Motions for Structural Response

W. D. Iwan
California Institute of Technology

Traditionally, most engineers have thought of earthquake accelerograms as resembling a broad-banded random process. This understanding was based on observations of ground motion records that were largely obtain from measuring stations that were located a substantial distance from the earthquake source. For such types of ground motions, the response of a structural system tends to build up gradually with a frequency and shape that approximate those of the fundamental mode of the structure. Beginning with the Landers earthquake of 1992, strong motion data began to be recorded from near-field stations located within a few kilometers of the plane of fault rupture. These ground motions were observed to differ dramatically from their near-field counterparts. Among other things, they were characterized by distinct large-amplitude velocity pulses. Such ground motions can give rise to structural response that more nearly resembles a traveling wave within a structure than the resonance build-up of a single mode. This type of response behavior is not well represented by the simple SDOF structural model that is the basis for the well-known response spectrum and its derivatives such as the increasingly popular Acceleration Displacement Response Spectrum (ADRS).

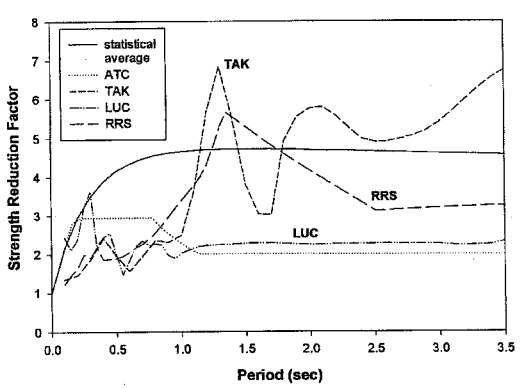
Recent changes in US procedures for earthquake design have attempted to account for the effects of near-field ground motions through the introduction of the near-field or near-source factors, N_a and N_v in addition to regular strength reduction factors used in conventional design approaches However, the basic design procedures employed have largely been based on studies using far-field ground motions. A preliminary study of the adequacy of these rules using measured near-field ground motions indicates that: *near-field factors, if employed, should be a function of the ratio of the predominant period of the structure to the predominant period of the ground motion rather than a function of the structural period alone.* Near field factors of the order of two are needed for period ratios less than one, while factors approaching unity are more appropriate for larger period ratios. Furthermore, based on inelastic behavior alone this study has shown that: 1) *existing inelastic strength reduction factors (excluding near-field factors) may be significantly unconservative for short period structures and overly conservative for long period structures,* and 2) *pulse-like near-field ground motions may cause structural response to be strongly biased (one-sided), thereby reducing the effectiveness of hysteretic energy dissipation.*

An alternative means of characterizing the demand of near-field ground motions is through the response of a simple shear-beam structural model. This approach is capable of depicting the wave-like structural response behavior that is associated with near-field ground motions. This approach may be used to construct a Shear-Drift Demand Spectrum (SDDS) which is a graph of the maximum base level mass-normalized inter-story shear force as a function of the maximum inter-story drift ratio. This spectrum is a continuous analog of the single-degree-of-freedom ADRS. The major conceptual difference between

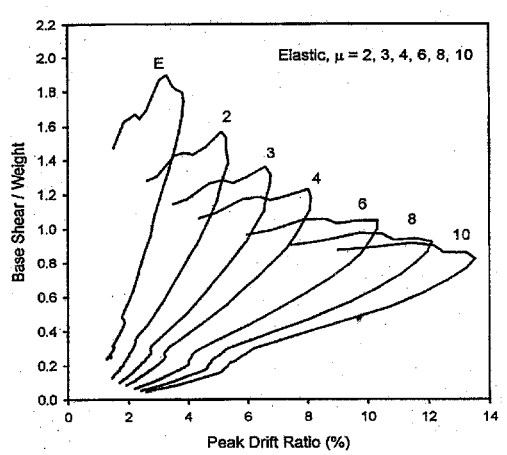
the SDDS and the ADRS is that the SDDS gives a measure of the *local* (inter-story) earthquake demand, while the ADRS gives a measure of the *global* (modal) demand. The SDDS can be combined with the results of a static pushover analysis in what might be referred to as the Drift Capacity Spectrum Method of structural analysis. This new method would be analogous to the Capacity Spectrum Pushover Method that is based on the ADRS.

There are similarities between the SDDS and ADRS, but it has been observed that there are also very significant differences; especially in the way inelastic structural behavior affects the two spectra. Studies of SDOF systems for far-field type earthquake ground motions have shown that the effects of inelastic structural behavior may be approximately accounted for by decreasing the effective natural frequency and increasing the effective viscous damping of the structure. In response spectrum based analysis procedures, such as the Capacity Spectrum Pushover Method, it is therefore assumed that inelastic structural behavior results in a reduction in demand. However, a recent study has shown that the effects of inelastic structural behavior on internal drift, as indicated by the SDDS, are just the opposite. It is observed that *inelastic structural behavior actually increases inter-story drift demand.* This is due to two factors: 1) for pulse-like inputs, relatively little energy is dissipated at peak response through inelastic action, and 2) once it has initiated, inelastic behavior tends to become concentrated locally within a structure. It is therefore concluded that *simple analysis procedures based on SDOF systems and the concept of equivalent linearization may not be appropriate for inelastic systems subjected to near-field type ground motions.*

Further research is urgently needed to more fully quantify the effects of near-field ground motions and develop simplified methods of analysis that accurately account for these effects. This research could most effectively be undertaken on a cooperative basis between the US and Japan.



Strength Reduction Factors (ATC does not include near-field factors)



Inelastic Shear-Drift Demand Spectrum (SDDS)

Strong Ground Motion Prediction for Active Faults with High Earthquake Potential

Kojiro Irikura
Disaster Prevention Research Institute, Kyoto University

Many megacities in Japan have been developed in sedimentary basins surrounded by seismogenic active faults and close to offshore subduction zones. They have repeatedly suffered from large earthquakes. The mitigation of earthquake damage in such cities requires strong motion prediction considering source effects due to the inland and subduction-zone earthquakes and propagation-path effects due to complex geology from source to sites.

In this report, we discuss where are causative faults during the 1995 Kyogo-ken Nanbu, Kobe, earthquake and how are faulting histories of the Arima-Takatsuki-Rokko fault system including the causative faults. Although detailed investigation of the active faults was made after the earthquake, we realized that practical earthquake prediction technique is not satisfactory yet for earthquake disaster mitigation. Second, we study how were strong ground motion near the causative faults and why such destructive motions were generated being offset from the faults. The validity and applicability of strong ground prediction and the relation between strong ground motions and structure damage are examined in comparison with the observed records and actual damage during the 1995 Kyogo-ken Nanbu (Kobe) earthquake. For testing the methodology of strong motion prediction, we take up the Osaka prefecture, which is adjacent to heavily-damaged areas during the 1995 Kyogo-ken Nanbu earthquake and surrounded by several active faults with high potential like the Kobe area.

We take up Osaka, one of the biggest cities in Japan, to estimate strong ground motion for hypothetical large earthquakes representing a potentially serious seismic damage. We study M7 inland event on seismogenic faults located near the basin edges and M8 subduction-zone events along the Nankai-Trough of South-Western Japan. We have successfully developed the empirical Green's function method to estimate strong ground motion for large earthquakes using observed records from small events occurring near the source area of the large event (Irikura, 1986). The small event records are superimposed to follow the scaling relations of the source dynamics. However, there are two problems to apply this method. One is that we have no appropriate records in most of cases. The other is that slip and slip velocity are not uniform in the rupture areas for large earthquakes more than 7. To solve the former problem, we introduce the synthetic Green's functions instead of the observed records for the empirical Green's functions. We calculate the small event records using a hybrid scheme, deterministic and stochastic approaches. For low frequency motion less than 1 Hz, we calculate small event records considering a double couple point source in the 3-D structure from source to site using a 3-D finite difference method. For high frequency motion more than 1 Hz, we simulate ground motion from the small event with the same size as the lower frequency motion using the stochastic method by Boore (1983). For the latter problem, we use the asperity source model by the statistical analysis of slip distributions from the waveform inversion of the source

processes for recent earthquakes. Then we compute strong ground motion from large earthquakes for the target source areas using the simulated small event motions as the empirical Green's functions and the asperity source model with heterogeneous slip distributions.

The validity and applicability of strong ground prediction and the relation between strong ground motions and structure damage should be examined in comparison with the observed records and actual damage during the 1995 Kyogo-ken Nanbu (Kobe) earthquake and recent damaging earthquakes world-wide.

Development of an Improved Parameterization of Near-Fault Ground Motions

Paul Somerville
Woodward-Clyde

The propagation of fault rupture toward a site at a velocity close to the shear wave velocity causes most of the seismic energy from the rupture to arrive in a single large long period pulse of motion that occurs at the beginning of the record (Somerville et al., 1997). This pulse of motion, sometimes referred to as "fling," represents the cumulative effect of almost all of the seismic radiation from the fault. The radiation pattern of the shear dislocation on the fault causes this large pulse of motion to be oriented in the direction perpendicular to the fault strike, causing the strike-normal peak velocity to be larger than the strike-parallel peak velocity.

The effect of forward rupture directivity on the response spectrum is to increase the level of the response spectrum of the horizontal component normal to the fault strike at periods longer than 0.5 seconds (Somerville, 1996, 1997). This causes the peak response spectral acceleration of the strike-normal component to shift to longer periods, for example from 0.25 seconds to as much as 0.75 seconds. Near fault effects cannot be adequately described by uniform scaling of a fixed response spectral shape; instead the shape of the spectrum becomes richer in long periods as the level of the spectrum increases.

Although the response spectrum provides the basis for the specification of design ground motions in all current design guidelines and code provisions, there is a growing recognition that the response spectrum alone does not provide an adequate characterization of near-fault ground motions. This is because near fault ground motions are characterized by a relatively simple long period pulse of strong motion having relatively brief duration, rather than by a stochastic process having relatively long duration that characterizes more distant ground motion. Unlike the case for more distant ground motion, the resonance phenomenon that the response spectrum is designed to represent has no time to build up when the input is a near-fault pulse. The response spectrum is thus not capable of adequately describing the seismic demands presented by a near-fault pulse.

Non-linear structural response analyses, including the use of time history inputs, will be required to meet the goals of performance based design. It is well known that different ground motion time histories that all match the same response spectrum produce variations in the response of a structure subjected to non-linear time history analysis. When the input time history is a near-fault pulse, this effect is accentuated to the point where small modifications of a near-fault time history that have no significant effect on the response spectrum can have a major effect on the response of a structure when subjected to non-linear time history analysis.

This demonstrates that the current standard of practice does not provide a reliable basis for providing near-fault ground motion time histories that are specified solely on the basis of a design response spectrum.

In the following, we outline an approach to developing an improved characterization of near-fault ground motions that supplements the response spectrum with time domain parameters such as the duration and amplitude of the near-fault pulse, and the energy and power input that it presents. This approach requires the interaction of strong motion seismologists and structural engineers.

- Assemble a large set of near-fault ground motion time histories that represent the range of expected behavior of near-fault ground motions

The ground motion time histories should represent not only ranges of parameters that are currently used in predicting strong ground motions, such as magnitude, distance from the earthquake source, and geologic site conditions, but also ranges of other parameters that are known to influence near-fault ground motion characteristics. These include the distance and azimuth from fault strike between the point of rupture initiation and the site, and the rise time (duration of slip on the fault). To augment the data set of near-fault strong motion recordings, especially for larger magnitudes and closer distances than are available in the recorded strong motion data set, and to provide estimates of the effect of source parameters on near-fault ground motions, we need to use broadband simulations of near-fault ground motion time histories.

- Identify Damaging Characteristics of Near Fault Ground Motions

By performing a large number of non-linear dynamic structural analyses using the large set of ground motion time histories, identify the time histories that are most damaging to structures, and identify the characteristics of the near-fault pulse that are most damaging to structures.

- Develop an Improved Parameterization of Near-Fault Design Ground Motions

Use the ground motion characteristics that are most damaging to structures to develop an improved parameterization of near-fault ground motion. The ground motion parameters may include time domain parameters that describe the near-fault pulse, such as its period and amplitude, in conjunction with parameters describing energy or power input, as well as parameters that describe the spectral content such as Fourier amplitude or response spectral amplitude. Confirm that structural response is sensitive to variations in these parameters.

- Develop a Near-Fault Ground Motion Prediction Model

Develop a model for predicting the ground motion parameter values of the improved parameterization from earthquake source parameters. The earthquake source parameters used to predict the ground motion parameter values, beside including the conventional ones of magnitude, distance, and site conditions, should also include parameters that are known to influence near-fault ground motion characteristics. These include the distance and azimuth from fault strike between the point of rupture initiation and the site, and the rise time (duration of slip on the fault).

- Develop a Near Fault Pulse Generation Algorithm

Develop an algorithm which allows the ground motion parameters to be represented in a suite of three pulses (for the strike-normal, strike-parallel and vertical components of motion) which satisfy the pulse duration, amplitude, energy and power input, and Fourier or response spectral ordinates specified by the model.

- Validate the Near-Fault Ground Motion Model

Test the adequacy of the ground motion model by confirming that the response of structures to the ground motions for specified combinations of magnitude, distance and site conditions is compatible with that obtained from available strong motion recordings having similar values of magnitude, distance and site conditions.

References

Somerville, P.G. (1997). The characteristics and quantification of near fault ground motion. Proceedings of the NCEER Workshop on National Representation of Seismic Ground Motion for New and Existing Highway Facilities, San Francisco, May 29-30, 1997.

Somerville, P.G., N.F. Smith, R.W. Graves, and N.A. Abrahamson (1997). Modification of empirical strong ground motion attenuation relations to include the amplitude and duration effects of rupture directivity, *Seismological Research Letters.68, 180-203.*

Somerville, P.G. (1996). Forward rupture directivity in the Kobe and Northridge earthquakes, and implications for structural engineering. *Seventh U.S. -Japan Workshop on Improvement of Structural Design and Construction Practices, Lessons Learned from Kobe and Northridge,* Jan. 18-20, 1996, Kobe.

Modeling of Phase Characteristic of Design Earthquake Motion

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Introduction

Modeling the phase characteristics of earthquake ground motion is important for the synthesis of design earthquake motion consistent with the given response spectra. This paper presents a simple method to model phase characteristics of earthquake motion using the concept of group delay time.

Modeling of Earthquake Ground Motion

If we can assume that the earthquake ground motion $o(t)$ can be expressed by the convolution of the three time functions; 1) the time delay caused by rupture propagation on the fault plane which is assumed to be expressed by a train of impulses $p(t)$, 2) the seismic source function $g(t)$, and 3) the effect of path of transmission $h(t)$, then we obtain $o(t) = p(t) * g(t) * h(t)$. If the function $p(t)$ is expressed by

$$p(t) = \sum_{i=1}^{N} a_i \delta(t - t_i) \tag{1}$$

in which a_i and t_i are an intensity and an arrival time of ith impulse. The Fourier amplitude spectrum $A_p(\omega)$ and the phase spectrum $\phi_p(\omega)$ are given as follows:

$$A_p(\omega) = \left(\sum_{i=1}^{N} a_i \cos(\omega t_i)\right)^2 + \left(\sum_{i=1}^{N} a_i \sin(\omega t_i)\right)^2, \ \phi_p(\omega) = \tan^{-1}\left(-\frac{\sum a_i \sin(\omega t_i)}{\sum a_i \cos(\omega t_i)}\right) \tag{2}$$

The group delay time for this train of impulses is obtained as

$$\frac{d\phi_p(\omega)}{d\omega} = \frac{-\sum_{i=1}^{N} a_i^2 t_i - \sum_{i=1}^{N} \sum_{j=i+1}^{N} a_i a_j (t_j + t_i) \cos\{\omega(t_j - t_i)\}}{\sum_{i=1}^{N} a_i^2 + 2\sum_{i=1}^{N} \sum_{j=i-1}^{N} a_i a_j \cos\{\omega(t_j - t_i)\}} \tag{3}$$

Modeling of Phase Characteristics Due to the Rupture Process

The rupture process expressed by the train of impulses $p(t)$ is obtained by subdividing the fault plane into several small fault elements and being concentrated the rupture energy of small event at the center of the each subdivided fault. Therefore the group delay time expressed by Eq. (3) is a representation of the phase shift due to the rupture process on the fault plane. If the value of $a_i a_j / \sum a_i^2$ is assumed to be small we can derive

$$\frac{d\phi_p(\omega)}{d\omega} \approx -t_p - \sum_{i=1}^{N}\sum_{j=i+1}^{N}\left(a_i a_j \Big/ \sum_{l=1}^{N} a_l^2\right)(\tau_i + \tau_j)\cos\{\omega(\tau_j - \tau_i)\} \tag{4}$$

in which

$$t_p = \sum_{i=1}^{N} a_i^2 t_i \Big/ \sum_{i=1}^{N} a_i^2 \,,\ \tau_i = t_i - t_p \,,\ \tau_j = t_j - t_p \tag{5}$$

and t_p is the average arrival time of the train of impulses.

If the number of impulses becomes very large we can assume

$$a_i \Big/ \sqrt{\sum a_i^2} = f(\tau)d\tau \tag{6}$$

in which the function $f(\tau)$ is an envelope time function of the train of impulses and $f(\tau)d\tau$ the intensity of the impulse at time τ. Substituting Eq. (6) into Eq. (4) we obtain

$$\frac{d\phi_p(\omega)}{d\omega} = -t_p - \int_\tau^\beta f(\tau)\int_\alpha^\beta f(\xi)(\tau + \xi)\cos\{\omega(\xi - \tau)\}d\xi d\tau \tag{7}$$

When the intensity of impulses is a constant form time α to β the integration of Eq. (7) is expressed as follows:

$$\frac{d\phi_p(\omega)}{d\omega} = -t_p - \frac{(\alpha + \beta)}{\omega^2}\{1 - \cos(\omega(\beta - \alpha))\}$$

Modeling of Phase shift Due to the Transmitting Path

The amplitude of frequency transfer characteristics of transmitting path and amplification effect due to the local soil condition is assumed to be given and defined by $A_h(\omega)$. The phase spectrum $\phi_h(\omega)$ is assumed to be derived by the minimum phase transfer function of $A_h(\omega)$. This assumption is not valid when the seismic wave has multiple paths between the observation point and the seismic source but for the simplicity this assumption is applied. Then the phase spectrum is derived by using Hilbert transformation relation existing between the amplitude spectrum and phase spectrum as follows:

$$\phi_h(\omega) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{\ln(A_h(y))}{\omega - y}dy \tag{8}$$

The group delay time is calculated by taking the derivative of Eq. (8) with respect to ω

$$\frac{d\phi_h(\omega)}{d\omega} = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{\ln(A_h(y))}{(\omega - y)^2}dy \tag{9}$$

Using FFT the integration of Eq. (9) can be performed easily by using the following pair of Fourier and Inverse Fourier transformations

$$-2/\omega^2 \Leftrightarrow |t| \tag{10}$$

Taking inverse Fourier transform of $\ln(A_h(y))$ and multiplying $-\frac{1}{2}|t|$, then taking Fourier transform of that value we can derive the left hand side of Eq. (9), i.e. group delay time.

Conclusion

A method to model the group delay time of a train of impulses was proposed. The phase shift due to the transmitting path of seismic wave motion is also expressed by the minimum phase transfer function of the amplitude spectrum of frequency transfer function of the path. Because the intensity at zero circular frequency of the Fourier spectrum of the train of impulses coincides with the seismic moment of an earthquake we can model the phase characteristics of an earthquake motion provided the rupture process of earthquake.

Level 2 Ground Motions for Civil Engineering Structures

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L2 Ground Motions Proposed by JSCE

Following the 1995 Hyogoken-nanbu earthquake, Japan Society of Civil Engineers (JSCE) issued "Proposal on Earthquake Resistance for Civil Engineering Structures". According to the proposal, two types of earthquake ground motions should be taken into account in earthquake resistant design of the structures. One is Level 1 (LI) motion of moderate intensity which is likely to experienced by the structures once or twice during their life time, and the other is Level 2 (L2) motion of extreme intensity rarely experienced during their life time. Despite many difficulties expected in the current state of knowledge and technology, L2 motions generated by active inland faults are, in principle, determined based on identification of threatening active faults and estimation of their fault mechanism. Since L2 motions are basically used to check an ultimate capacity of structures beyond their elastic limits, time histories of the ground motion are needed to be evaluated.

Evaluation Procedure

In Japan, both intraplate and interplate earthquakes should be equally taken into consideration in the evaluation of L2 motions, paying attention to the difference in their nature. For example, it is generally said that return periods of the interplate earthquakes are a few hundred years while those of the intraplate earthquakes are over a thousand years. Thus, L2 motions from intraplate earthquakes are mainly evaluated from geological data of active faults. As hidden faults are not included in the present fault data and they are threatening to cause inland earthquakes anywhere in Japan, a minimum L2 motion is needed even in an area where significant active faults are not mapped until today.

Moreover, structural responses vary significantly with predominant periods in the input motions, vibration periods of a structure are one of the key factors in selection of seismic faults for L2 motion as well as in selection of a reference bedrock where a standard L2 motion is defined. When the seismic faults and the ground model are determined, L2 motions can be evaluated by existing methods such as theoretical, semi-empirical and empirical methods. However, as the fault mechanism of future earthquakes is unpredictable, parametric studies are almost inevitable to find a range of possible variation of the L2 motion for the time being.

Selection Of Nearfield Scenario Earthquakes For Zonation – Consideration From Case Studies In Hokkaudo, Northern Japan

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Introduction

Kobe Earthquake of 1995 occurred just beneath the urbanised area and caused severe damages in Kobe and its vicinities. Maximum intensity of the affected area was 7 in JMA Scale (X-XII in MM Scale), which was the first experience in Japan because the intensity 7 was defined after the Fukui Earthquake of 1948. This earthquake also occurred inland and almost 100% houses were destroyed in wide area because of high intensity. Almost 50 years we had no experience of such high intensity as 7 in JMA Scale and had almost forgotten the occurrence of such violence inland earthquakes. Our main concern had been concentrated into the interplate huge earthquakes of magnitude 8 class, like Kanto Earthquake of 1923. Therefore such huge interplate earthquakes have been considered as scenario earthquakes for disaster mitigation programs in each local government. The occurrence of Kobe earthquake changed this situation in drastic and an importance of moderate size but just below earthquakes had been recognised for scenario earthquakes (Kagami, 1997).

In this paper newly raised problems in selection of scenario earthquakes are discussed through case studies in several cities in Hokkaido.

Seismic Environment of Hokkaido

First of all, I would like to introduce seismic environment in Hokkaido. It is the biggest prefecture in Japan (22% of area but 4.7% population of the whole Japan) and consist of one measure island of Hokkaido and several small islands. Hokkaido island is situated on the North American Plate which is compressed by two measure plates of Pacific and Eurasian. Therefore at the southeastern part, the Pacific Plate is subducting under the island and causes huge earthquakes of magnitude 8 class. At the western part, Eurasian plate pushes Hokkaido island and causes large earthquakes too such as Hokkaido Nansei-oki earthquake of 1993 (Kagami, 1995). Inland intraplate earthquakes are also significant in Hokkaido and many active faults traces are pointed out. Therefore we should select scenario earthquakes considering these circumstances.

Key Points in Zonation for Near-Field Earthquake

In zonation an estimation of spatial distribution of ground motions is the basic procedure for succeeding risk evaluations of buildings, facilities and so on. Spatial distribution of input motions is estimated by assuming the focal plain and its parameters of scenario earthquake. In the case of interplate earthquake, an epicenter is located at rather far place in general and differences of epicentral distance is almost same in urban area. Therefore an contribution of site soil conditions to spatial distribution of seismic input is significant.

In these cases, location of fault and focal parameters are not so influential for spatial pattern of input motions and therefore that of damage distribution. In 1993 we experienced two earthquakes of Kushiro-oki and Hokkaido Nansei-oki in Sapporo of their intensity were 4 in JMA scale and made detailed intensity distribution maps by questionnaire method. These two maps show very similar pattern each other in spite of quite different epicenters. This means that the spatial distributions indicate difference due to site soil conditions. On the contrary, in the case of nearfield intraplate earthquakes distance from fault plain and its direction are more influential to spatial distributions than subsoil conditions. Therefore, an estimation of size and location of fault plain control strongly those spatial distributions. Another source parameters such as rapture direction, rapture velocity are also important factor to characterise their spatial pattern.

Case Studies in Hokkaido

The author have been contributed for estimation of scenario earthquakes in three major Hokkaido cities of Sapporo, Hakodate and Asahikawa, as a member of the earthquake mitigation committee for each local government. From these experiences estimation process and its problems are discussed here. Three cities have different conditions of certainty of locations of earthquake cause faults.

a) Location of seismic fault is well known case (Hakodate)

The first case is the earthquake cause fault is well known from surface trace. In case of Hakodate city, there is a known surface fault about 10 km west of the city. This fault is recognised as active one and after the Kobe event trench investigation has been started. Small earthquakes also occurred along the faults and this suggests future damaging earthquake will occur by this fault. In this case, estimation of future scenario earthquake can be done easily and uniquely. We estimated scenario earthquake as follows; fault plain 20 × 10 km, M=6.5. Hakodate city is the third biggest one in Hokkaido and suffered earthquake damage several times by far field interplate earthquakes. Liquefaction damages were predominated in the coastal area and inundated by tsunami.

b) Location of hidden fault is not obvious case (Sapporo)

The second case is earthquake cause faults are not appear on the surface and an estimation of exact location of the fault is not easy. In the case of the Sapporo city, no surface fault traces is known on the city but activities of small earthquakes tell us an existence of hidden earthquake fault. However, location of candidate fault plain is not obvious and cannot be determined these parameters in deterministic way. Therefore, multiple cases should be prepared changing fault location and related parameters. For these multiple models various spatial distributions can be estimated and in general these show quite different pattern each other. To make scenarios for disaster management it is a key point how select typical cases among various possibilities. For the decision making, different criterions of seismological, engineering and administrative point of views should be coordinated.

c) No fault is known case (Asahikawa)

The third case is no fault is found around the urbanised area and no hidden faults are also inferred by microearthquake activities. Asahikawa city corresponds to this case. Asahikawa city is located in the central part of Hokkaido and is far from coastal lines. Therefore this city is less influence of huge interplate earthquakes. As for near field earthquake, there is no surface fault trace around the city. Activity of micro earthquake is not so high and lineament of epicenters is not found which suggests an existence of hidden fault. Therefore, an imaginary fault was taken as for scenario earthquake considering worst case. Location of the fault was estimated at the foot of mountain range near downtown considering geological conditions and its effects to the city.

Concluding Remarks

Kobe earthquake gave us an opportunity to check and revise of earthquake disaster mitigation programs. For the first stage an estimation of nearfield scenario earthquakes is important task. In this paper, problems are discussed through the case studies in Hokkaido, northern Japan and indicated three cases for selection of scenario earthquakes corresponding to the situations of surface fault traces.

References

Kagami,H.(1995). Lessons Learned from the Three Large Damaging Earthquakes in Hokkaido, Northern Japan Occurred from 1993 to 1994, Proc. 4th Japan/US Workshop Urban Earthquake Hazard Reduction, 1-10.

Kagami,H.(1997). Seismic Risk Evaluation in Hokkaido, Northern Japan. -Recent Trend before and after the Kobe Earthquake, 1995, Proc. 5th Japan/US Workshop Urban Earthquake Hazard Reduction, 123-126.

Earthquake Damage of Reinforced Concrete Buildings

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Reliable statistics about damaged and undamaged buildings are important to establish disaster reduction measures against future earthquakes. Some comprehensive statistics were obtained after the 1985 Mexico Earthquake, the 1990 Luzon (Philippines) Earthquake, the 1992 Erzincan (Turkey) Earthquake and the 1995 Hyogo-ken Nanbu (Kobe) Earthquake by the Architectural Institute of Japan (AIJ).

The AIJ Investigation teams studied the affected area from each earthquake and identified heavily damaged zones. A group of two to three experienced structural engineers and researchers studied the damage of buildings in each area, where the group went through all alleys and investigated the damage of every building from the external appearance. The damage to low-rise buildings (less than 5 stories) was relatively light, whereas the damage was heavier in mid- to high-rise buildings in all the disasters.

A series of single-degree-of-freedom (SDF) systems were designed using the governing building code in the affected area. The nonlinear response of SDF systems was calculated under earthquake motions recorded near the area of the inventory damage surveys after the 1985 Mexico Earthquake, the 1992 Erzincan Earthquake, and the 1995 Hyogo-ken Nanbu Earthquake. The nonlinear SDF earthquake response indicated that the systems designed with small ductility and large yield resistance developed small ductility demand, whereas the systems designed with large ductility and small resistance developed a significantly large plastic deformation.

A significant difference existed between the observed damage statistics and the calculated ductility demands. If the structures were to possess the lateral resistance required by the code, and if the structures were to fail at the design ductility, most of low-rise buildings must have failed in these earthquakes. On the contrary, the observed damage statistics showed significantly smaller damage in the low-rise building.

The following points may be stressed to explain the discrepancy between damage statistics and calculated ductility demand.

(1) Effective Earthquake Motions: The effective ground motion may be much less than the recorded. The damage of buildings around the Fukiai Station in Kobe or the SCT building in Mexico City, the damage of buildings was much lighter than the response calculations implied.

(2) Global to Local Damage: The response of an SDF system indicates an average damage rate of a building. The local damage could be significantly larger than the SDF ductility demand.

(3) Design Earthquake Forces in Code: The building might possess lateral resistance much higher than the code specified value due to the existence of non-structural elements and the additional resistance associated with structural design (additional materials, safety factor in material strength, additional structural elements, etc.). A structure can normally develop lateral resistance at the formation of a collapse mechanism higher than that specified by the design code.

(4) Ductility Requirements in Tall Buildings: It should be noted that the demand for reduction in design earthquake load is not the same for low-rise and high-rise buildings in real life; i.e., larger reduction is normally needed in the design of a taller building.

(5) Effect of Additional Resistance: Furthermore, an additional lateral load resistance, for example, provided by non-structural walls, also influence the earthquake response. The increase in lateral load resistance by non-structural as well as structural elements is more pronounced in the lower building, and the additional resistance in the low building could further reduces the plastic deformation during an earthquake.

Low- to mid-rise buildings could be designed for higher lateral load resistance using a smaller design ductility, and an appreciable lateral load resistance can be added to these structures from, for example, non-structural partitions. Therefore, a plastic deformation and associated damage could be significantly reduced in these structures. On the other hand, it is essential in the design of high-rise buildings to reduce the design earthquake loads as much as possible even counting on expected ductility, hence these tall buildings will develop intended plastic deformation and must suffer associated damage from an earthquake.

References:

Architectural Institute of Japan (1987), Reports on the Damage Investigation of the 1985 Mexico Earthquake (in Japanese), 599 pp.

Architectural Institute of Japan (1992), Reports on the Damage Investigation of the 1990 Luzon Earthquake (in Japanese), 396 pp.

Architectural Institute of Japan (1993), Report on the Damage Investigation of the 1992 Turkey Earthquake (in Japanese), 221 pp.

Reinforced Concrete Committee (1996), Damage Investigation Report on Concrete Buildings, the 1995 Hyogo-ken Nanbu Earthquake (in Japanese), The Kinki Branch, Architectural Institute of Japan, 245 pp.

Effects of Near-Field Ground Motion on Long Period Building Structures

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The results of an ongoing CUREe-Kajima research project on near-field effects will be summarized. The emphasis in the first year of this study is on achieving a basic understanding of the attributes that characterize near-field ground motions and their effect on the response of elastic and inelastic SDOF and MDOF structural systems. More specific, the question is what sets these ground motions apart from "standard" ground motions whose effects on the response of structures has been considered, either explicitly or implicitly, in presently employed design procedures.

In order to address these issues, extensive studies with elastic and inelastic structural systems subjected to pulse-type and recorded as well as simulated near-field ground motions are carried out. Pulses of well defined shapes are utilized to relate ground motion parameters (PGA, PGV, PGD, and pulse period T_p) to structural parameters (period, base shear yield strength, and strength distribution over height), and to gain a basic understanding of input and response characteristics. Near-field records are utilized to identify salient structural response characteristics and to relate the response to pulses with the response to actual records.

At this time the study has not progressed far enough to draw general and strong conclusions. Many findings noted by others have been confirmed, and new but preliminary findings have been discovered. These preliminary findings, some of which may be subject to change through a more detailed study, can be summarized as follows:

- The pulse-type characteristics of many near-field ground motions can be identified in the time history traces of velocities and displacements, in the shape of the response spectra, and in other spectral quantities such as the ratio of NHE/μ_{cyc}. More work needs to be done to relate near-field ground motion characteristics to the characteristics of basic pulses so that advantage can be taken of general information derived from detailed response studies of SDOF and MDOF systems subjected to pulse inputs.

- In many aspects the response of structures to pulse inputs differs greatly from that to standard ground motions. For elastic structures with a fundamental period T exceeding the pulse period T_p, the story shear force distribution over the height is very sensitive to the ratio T/T_p and may cause shear forces in middle or upper stories that are higher than the base shear. Unless this is considered in strength design, these middle or upper stories will yield prematurely. On the other hand, for structures of low strength in which the ductility demands are high, the largest ductility demands migrate to the bottom stories of the structure.

- For structures that are designed according to present design procedures (without regard to near-field effects) the ductility demands will vary greatly over the height of the structure and will be quite different from the demands imposed by standard ground motions. The demands will depend strongly on the ratio T/T_p. The ductility demands may be much higher than anticipated (based on presently accepted design philosophy) if the fundamental period is in the critical T/T_p range.

- In many period ranges (not only for $T/T_p > 1.0$) the P-delta effect plays a critical role. Ductility demands may be greatly amplified if any story has a negative post-yield stiffness, even if the negative slope is only a small fraction of the initial elastic stiffness.

- Based on the preliminary findings of this study a greatly modified design approach is needed for flexible structures in regions in which near-field ground motions dominate the seismic hazard. This problem cannot be solved effectively by applying a near-field factor to the base shear and using the same shear force distribution over the height as is used in present design procedures.

Conventional Reinforced Concrete Frames and "Near-Field" Motions

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This is a brief note on a study to explore the question, "Will conventional reinforced concrete frames behave properly if subjected to near-field ground motions?" Strictly, the question does not refer to a building but to a two-dimensional model with nonlinear hysteresis (Takeda) and to an ensemble of eight acceleration/time histories. We start with two premises not amenable to being proven in one page: (a) that the selected reinforced concrete frames have the properties to behave properly in ground motions of the El Centro 1940 class normalized to 0.5G and (b) that the records selected by Iwan (1) represent the proper near-field ground motions.

We consider three reinforced concrete frames with 5, 11, and 17 ten-ft. stories proportioned to have initial calculated periods of 0.5, 1.1, and 1.6 sec. The column sizes for these frames are 26, 30, and 36 in. square. The girders, spanning 30 ft., are 30 in. deep. The base shear strength coefficients of the frames are 0.25, 0.12, and 0.07, respectively, for the frames with 5, 11, and 17 stories. The responses of these frames to the ground motions listed in Table I are analyzed using a nonlinear analysis program.

Before considering the results of the nonlinear analysis, it is of interest to look at the linear displacement spectra (damping factor = 2%) shown in Fig. 1 for the eight records. Considering that an idealized displacement spectrum defined simply by D = 10T, where T is in seconds and the displacement, D, is in inches, will provide a reasonable upper bound to most ground motions anticipated by conventional wisdom, it is clear that the results of the nonlinear analysis for near-field motions are not likely to be positive.

Figure 2 shows the calculated mean drift ratios for the three frames (ratio of roof maximum roof drift to height of frame). If the objective of design is to do a minimum of damage to building contents, the results are not acceptable. Nor are they predictable on the basis of the displacement response spectrum defined by D = 10T. Because of the linear relationship between nonlinear displacement response and ground-motion intensity, we can estimate what would happen if we redesigned the frames in anticipation of the displacement spectra shown in Fig. 1 simply by using the same frame models but by normalizing the ground motions to suit D = 10T. Results of this evaluation are indicated in Fig. 3.

To attain the results in Fig. 3, the frames need to be redimensioned to have calculated periods equal to or less than 40% of those indicated above, if the criterion is drift control. If that is too expensive a solution, to tolerate calculated drifts of 4% is an option for reinforced concrete frames. It is not a threat to the structure but it does imply that the building will be a total loss if the near-field motion occurs. Admittedly, the conclusion is one in the

domain of arithmetic. We need to re-evaluate the past evidence and be sensitive to this question in the future before we inflate the design requirements.

TABLE 1: Ground Motions Recorded during the Northridge 1994 Event

Identification	Rinaldi Receiving Station		Sylmar Conv. Station		Sylmar Conv. Station – E		Sylmar County Hospital	
	RRS.1	RRS.2	SCS.1	SCS.2	SCSE.1	SCSE.2	SCH.1	SCH.2
Max. Acc. cm/sec^2	473	823	584	734	808	485	592	863
Soil	Alluvium		Alluvium		Sedimentary Rock		Alluvium	

1. Wilfred D. Iwan, "Near-Field Considerations in Specifications of Seismic Design Motions for Structures," Proc., Tenth European Conference for Earthquake Engineering, 1997. (Ground-motion records extracted from CIT-SMARTS. Strong Motion Center, California Institute of Technology.)

Acknowledgment: Analyses were made by JoAnn Browning, Graduate Student at Purdue University, as part of a project sponsored by the NSF Program for Earthquake Hazard Mitigation.

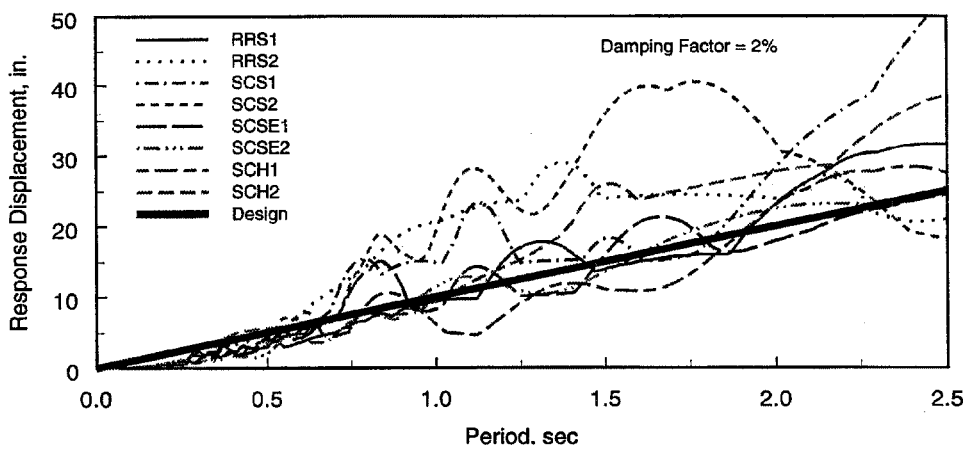

Fig. 1 Displacement Response Spectra

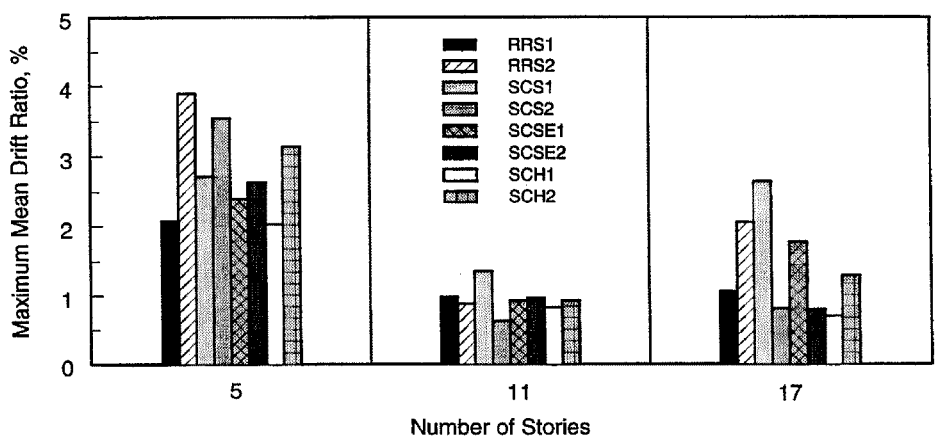

Fig. 2 Maximum Response to Near-Field Ground Accelerations

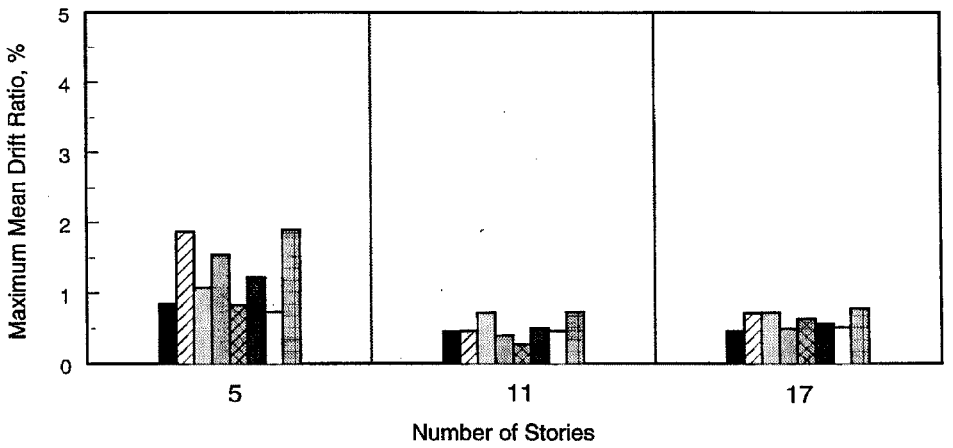

Fig. 3 Maximum Response to Scaled Near-Field Ground Accelerations

Influence of Vertical Ground Motion on the Response of Precast Parking Garages

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Introduction

In general, precast parking garages performed very poorly during the 1994 Northridge earthquake. Two modern garages in the immediate epicentral area collapsed, and many others experienced severe damage. One set of investigators (Engelkirk and Beres, 1994) identified vertical accelerations as the primary cause of the two failures. The influence of vertical accelerations on the seismic response of this type of structure is investigated in this paper.

A simple model is used to represent the behavior of precast members subjected to vertical accelerations, and the model is verified using the measured response of a six-story parking garage located 31 km from the epicenter of the earthquake. Three near-field ground motion records are then used to estimate the response of the precast members in the collapsed parking garages.

Measured Response

Fourteen instruments recorded the response of a six-story parking garage located near downtown Los Angeles (Shakal, Huang, and Darragh, 1996). Structural walls formed the lateral-load resisting system in the building, and precast members formed the gravity system. Vertical accelerations were recorded at three locations: two at the base of a wall and one at midspan of a precast double tee at the roof level. Measured accelerations and integrated displacements are shown in Fig. I and 2, respectively. The amplitude of the accelerations at the roof were amplified by more than 2.5 relative to the base of the wall, and the records included a significant component at 3.9 Hz which was not contained in the base motion. The frequency component at 3.9 Hz may also be observed in the roof displacement record.

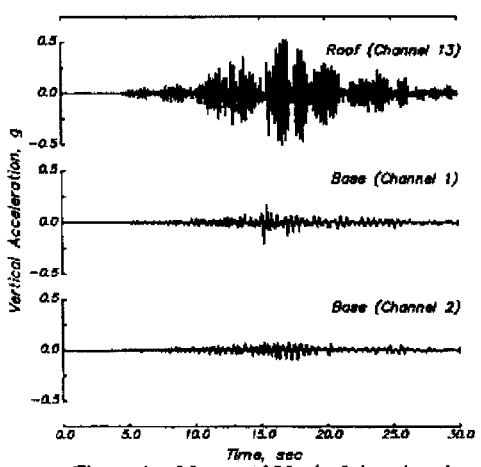

Figure 1 – Measured Vertical Accelerations in Six–Story Parking Garage

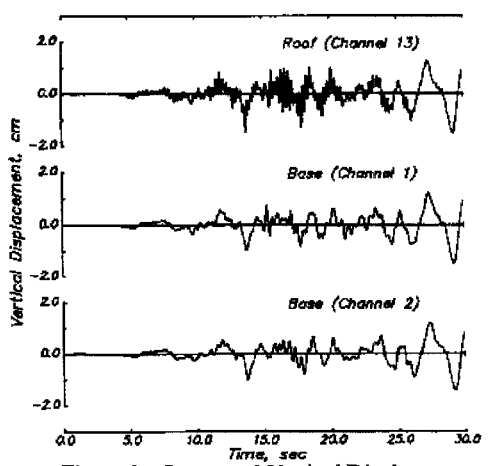

Figure 2 – Integrated Vertical Displacements in Six–Story Parking Garage

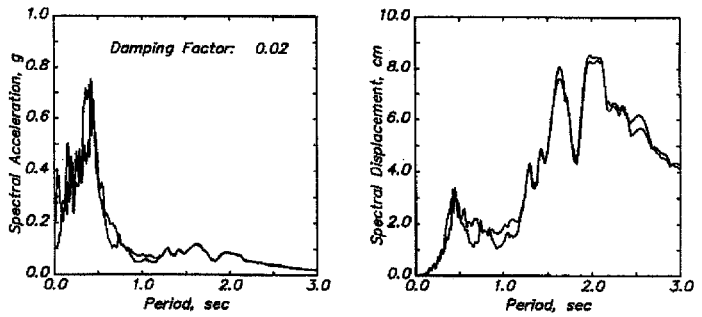

Figure 3 — Elastic Response Spectra for Vertical Motion at Base of Six-Story Building

Analytical Model

The double-tee beam was modelled as a continuous, uniformly-loaded, simply-supported member subjected to vertical base acceleration at the ends. Because only one structural frequency was observed in the measured response, a single mode was used in the calculations. The fundamental natural frequency was calculated to be 3.8 Hz using nominal material properties, which agreed with the measured response. Using the average of the spectral ordinates from the two ground records (Fig. 3) and assuming a sinusoidal mode shape, the maximum relative displacement of the beam was calculated to be 0.84 cm and the maximum acceleration of the beam was calculated to be 0.5 g. These values are within 5% of the corresponding values from the measured data. This observation implies that the vertical accelerations are not amplified in the columns over the height of the building.

Near-Field Vertical Accelerations

Large vertical accelerations were recorded in the epicentral region of the Northridge earthquake. The records from three stations that were located within 10 km of the epicenter are shown in Fig. 4. Peak accelerations exceeded 0.5g in all records. The corresponding linear response spectra for the records are shown in Fig. 5.

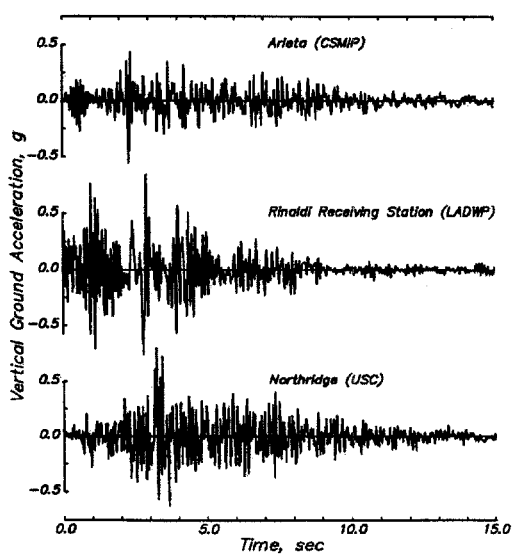

Figure 4 — Vertical Ground Motion Records at Near-Field Sites

Calculated Response Of Parking Garages In Epicentral Region

The seismic displacement, acceleration, and shear response of double tee and inverted tee beams from the collapsed parking garages were estimated using the response spectra shown in Fig. 5. Typical double tee beams had a span of 55 ft (17 m)

and a calculated natural frequency of 3.1 Hz. The typical span for inverted tee beams was 29.5 ft (9 m), and the corresponding frequency was 5.8 Hz. Calculated relative displacements were larger in the double tee beams, but did not exceeded 3 cm. Calculated maximum accelerations were approximately 3 g in both types of beams. The calculated seismic shears in the inverted tee beams were an order of magnitude larger than those in the double tee beams. The magnitude of these shears ranged between 50 and 75% of the factored design shear from live and dead load in the inverted tee beams.

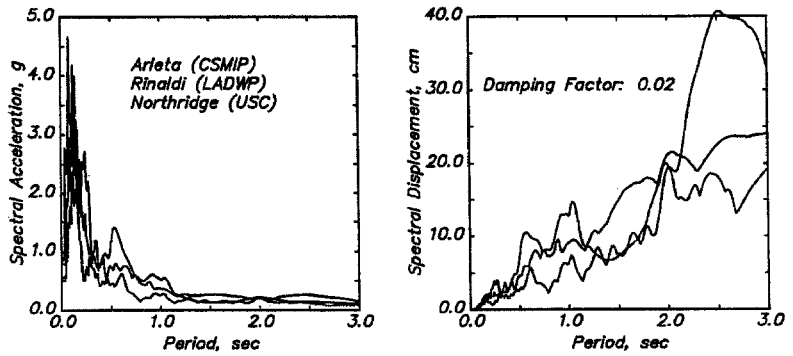

Figure 5 — Elastic Response Spectra for Vertical Motion at Near–Field Sites

Conclusions

The measured response of a six-story parking garage during the 1994 Northridge earthquake confirmed that precast members are excited vertically during strong ground motion. The measured dynamic response was well-represented by modelling the roof member as a simply-supported, continuous beam. High-intensity vertical ground motions were measured in the epicentral region of the Northridge earthquake. Large spectral accelerations were observed for periods less than 0.3 sec, and the natural frequencies of typical precast members were in this range. Calculated dynamic shears in typical inverted tee beams were considerably larger than design shears corresponding to factored gravity loads.

References

Engelkirk, R. E. and Beres, A. (1994). "The Need to Develop Shear Ductility in Prestressed Members," *Concrete International,* ACI, Vol. 16, No. 10, pp. 49-56.

Shakal, A. F., Huang, M. J., and Darragh, R. B. (1996). "Interpretation of Significant Ground-Response and Structure Strong Motions Recorded during the 1994 Northridge Earthquake," Bulletin, Seismological Society of America, Vol. 86, No. IB, pp. S231-S246.

Acknowledgment

Studies of the parking garages damaged during the 1994 Northridge earthquake were supported by the National Science Foundation, the Portland Cement Association, and the Precast/Prestressed Concrete Institute. The opinions expressed in this paper are not necessarily those of the sponsors.

Ductility and Strength Demand for Near Field Earthquake Ground Motion – Comparative Study on the Hyogo-Ken Nanbu and the Northridge Earthquake

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The Hyogo-ken Nanbu Earthquake of January 17, 1995 caused severe damage to buildings, highway bridges, railways, lifeline systems, port facilities, and so on. This event is the first instance in which engineering structures which were designed for the highest seismic forces in the world have been subjected to such destructive ground motions. This paper shows several calculated response spectra for the Kobe record and the Sylmar record obtained during the Northridge Earthquake, which occurred on exactly the same day of 1994. Together with these two recent near field earthquake motion, the El Centro record of the Imperial Valley Earthquake in 1940, and the Hachinohe record of the Tokachi-oki Earthquake in 1968 are compared. Obtained results are briefly summarized as follows.

1) The absolute acceleration response spectra for the Kobe and the Sylmar records show higher acceleration response than the El Centro and Hachinohe records in all period ranges. The response of the Kobe record shows more than 1g in the period range from 0.15 to 1.2 seconds. Especially in the 0.3 to 0.5 seconds range, the response even exceeds 2g. It is interesting to see that the Kobe and the Sylmar records show similar acceleration responses in almost all period ranges.

2) To examine the nonstationary power imported to structures with different natural periods, evolutionary power spectra for the four earthquake ground motion records are calculated and compared. The Kobe record shows a very high and sharp peak in power just after the beginning of the earthquake motion. This peak was felt as an extremely strong shock by local residents. Two strong peaks of the power are observed in the first several seconds, which could have contributed to the serious damage of structures. The Sylmar record also shows sharp peaks, but the level of the power is not as high as the Kobe record. Compared to the Kobe and the Sylmar records, the Hachinohe and El Centro records show a very low level of the power, even though the duration of strong motion is about 30 seconds long.

3) The inelastic displacement response spectra of a single degree of freedom structure with a perfect elasto-plastic bilinear hysteretic restoring force is calculated. Comparing with the corresponding linear displacement response spectra, the Kobe and the Sylmar records give much larger displacements in the short period range (0.1~0.7 seconds). This effect is due to the large plastic deformation caused by the high intensity, shock-type loading.

4) The elastic strength demand spectra with given ductility factor is calculated. For the Hachinohe and the El Centro records, the required elastic strength level for inelastic design with the allowable ductility factor 5 is around 0.2g or less, which matches with the

conventional earthquake design of buildings and bridges. However, for the Kobe and the Sylmar records, 0.4g is required as the elastic strength even with the allowable ductility factor 10, for the short period range (0.1~0.4 seconds). Hence, present elastic design level and allowable ductility factor both have to be raised up by at least a factor of two, otherwise extremely large damage can be expected due to shock-type loading. Urgent retrofit of old structures and re-examination of present seismic design codes are essential.

Effects of Near-Field Ground Motions and Hysteresis Type on the Collapse-Potential and Response of Buildings During Earthquakes

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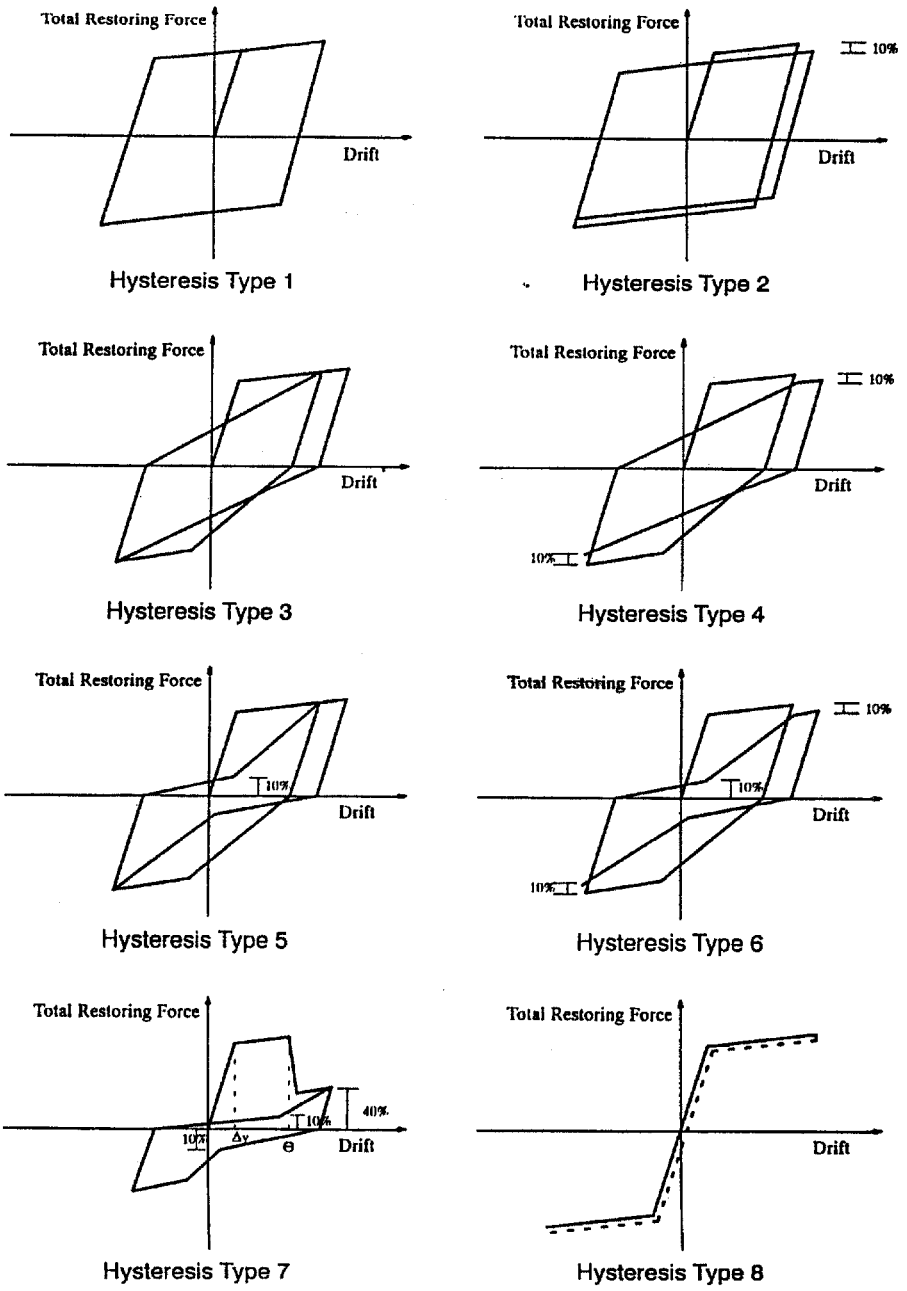
Two interesting phenomena were observed during the Northridge Earthquake that generated both concern and curiosity among practitioners and researchers. The first was the fracture in welded beam-to-column connections of steel moment frames. The second was the observation of large velocity pulses in ground motions measured in the epicentral region of the earthquake now referred to as near-field effects. The near-field motions, which were noted by Iwan and others after previous earthquakes, may have exacerbated the problem of the fractured connections. A research program funded by FEMA was begun shortly after the earthquake and aimed at developing methods to repair the damaged connections. This is sometimes referred to as the SAC Phase 1 project. After the completion of this program, a second research program, SAC Phase 2, was funded by FEMA to answer more fundamental questions concerning steel moment frame design and behavior.

The Performance Prediction and Evaluation Team which is part of the SAC Phase 2 program is charged with developing reliable design and evaluation procedures for welded steel moment frames. The PPE Team will use research results of other teams and their own to develop reliable analysis procedures and acceptance criteria. The acceptance criteria will be based on reliability concepts developed by Allin Cornell. The design and evaluation procedures will be performance based. One performance level will be collapse prevention. The seismic hazard for this performance is a 2% in 50 year ground motion. This aspect of the program is the focus of my presentation.

The SAC Phase 2 program will consider a number of different connections in addition to the pre-Northridge welded connection including bolted connections which may be rigid or partially restrained. Each connection type has a unique hysteresis behavior. The mathematical models representing the hysteresis behavior of many of these connections is shown in the figure below. These have been incorporated into the Drain-2DX computer program. The ideal behavior of these connections is modeled as bilinear and is shown in the upper left hand part of the figure. The other types represent strength and/or stiffness degrading systems and those that experience fracture.

The collapse potential of four of these systems will be discussed at the meeting. Analysis for 3- and 9-story buildings designed by the 1994 UBC and shaken by recorded near-field motions will be presented. Results for dynamic pushover analysis, a procedure developed by Cornell, will also be discussed.



Hysteresis types used in the study.

Post-Kobe Research in Japan on Steel Moment Frames and Their Beam-To-Column Connections

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Disaster Prevention Research Institute
Kyoto University

Both in the 1994 Northridge and the 1995 Kobe earthquakes, steel buildings sustained much damage, and many similarities in damage were disclosed. Some notable similarities are as follows:

(1) Steel buildings had not received much damage in the previous earthquakes, and for the first time in the history of steel constructions they sustained significant damage in those two earthquakes.

(2) Modem building structures designed and constructed with present practices were the major victims, meaning that we cannot blame old technologies but our current practices are in question.

(3) Much damage was disclosed, but practically none at least among those with the most recent practices collapsed.

(4) Many welded beam-to-column connections failed in fracture, indicating that connections were one of the weakest spots in steel moment frames.

With so many similarities in damage between the two earthquakes, there is a strong need of and a great benefit expected from a joint research effort between the two countries.

The more we looked into the damage, however, the more differences in nature and sources of damage were observed. Notable differences are summarized as follows:

(1) Beam-to-column connections failed in fracture, but in many instances of Japanese fractures beam plastification and local buckling were also observed, meaning that the beams dissipated some energy before fracture, whereas to the writer's knowledge, the vast majority of U.S. fractures involved almost no plastification in either beams or columns. The degree of plastic rotation capacity may be different between the two countries.

(2) Steel materials being used may also be different. For many years Japan has placed attention to the importance of material strain hardening for securing beam plastic rotation capacity, say, by specifying a maximum yield stress small enough relative to the ultimate strength. Common use of so called dual-purposed steels in the U.S. may be an indication of less concern on the role of material strain hardening in the U.S.

(3) Welding procedure is significantly different. Japan sticks to gas-shielded metal arc welding with solid wires, whereas the U.S. employs self-shielded flux cored welding.

Japanese welding is often conducted in the shop, whereas the U.S. welding are almost exclusively made in the field.

(4) Connection details are also different. Japan uses box columns, whereas U.S. uses wide-flange columns. This difference is accompanied by many differences in connection details, like web-welded in Japan versus web-bolted in the U.S. etc.

(5) The moment frame as a system is not the same. All beam-to-column connections are rigidly connected in Japan, whereas in the U.S. rigid connections are assigned only to selected locations. The degree of redundancy appears different.

(6) A different aspect, but worthy to note, is a significant difference in the amount of data obtained from the earthquakes. The writer learned that some steel buildings damaged in the Northridge Earthquake were instrumented, and ground motion and response records were obtained, which should be of a great help in assessing the damage. No steel building in Kobe was instrumented, and no ground motion was recorded at any site of damaged steel buildings, either. Japan encounters great difficulties in interpreting the damage.

What were the main sources that brought the damage to steel buildings. There was no single source, but the damage was given as a result of mixture of various sources related to design, materials, welding, connection details, and structural systems. The writer believes that this understanding is shared by Japan and the U.S. Then, how should we challenge these problems and upgrade the seismic design of our steel buildings? The focus, attention, and direction appear not to be the same in many aspects between the two countries.

(1) Use of materials with better ductility can be a solution toward better seismic performance of steel buildings. Japan has developed a new type of steels having a good margin between the yield and ultimate stresses, a smaller variation in these specified stresses, and a larger fracture toughness. Use of the new steels is likely to become mandatory in the near future. The writer does not have knowledge on what actions have been considered in the U.S. on this issue.

(2) Fractures at weld metals were very serious in the U.S., and use of different electrodes having a larger toughness and smaller deposition rate is now required in the U.S. In Japan fractures at weld metals were also disclosed in many instances, and welding with stringer bead placement in order to avoid too large heat input is now strongly recommended.

(3) The previous statement in [(2)] is associated primarily with quality assurance. The need is stated everywhere now, but specific measures to assure quality are yet to come in Japan. Welds are inspected ultrasonically for years. Passing the inspection, however, does not mean that welds are completely flawless. Post-Kobe experiments often revealed that early fracture occurred at welds even if they pass the UT inspection. To reevaluate the inspection regulations is a subject being considered in Japan. The writer wishes to know what actions have been made in the U.S. on the quality related issues.

(4) The writer learned that regarding the connection details the U.S. has come to a conclusion that moving the plastic hinge away from the beam end is the most secured way to improve the ductility capacity of beam-to-column connections. Such strengthening is considered as a possible solution also in Japan, but the general sentiment is that we can ensure sufficient ductility capacity just by modifying details. Many efforts are on going for modifying details like by the change in size and shape of weld access holes, etc.

(5) As to the structural system, Japan will not give up box columns and switch to wide flange columns at least for the foreseeable future. The writer wishes to know if the U.S. tries to increase the number of rigid connections to enhance redundancy.

Steel damage observed in the Northridge and Kobe Earthquakes was very similar, which immediately leads us to start thinking about a joint research effort, but significant differences in damage do exist as well, which were stemmed primarily from the differences in our design, fabrication, and construction practices (construction culture as a whole). As a result, Japan and the U.S. are heading for different directions in many aspects, although the goal (to achieve better seismic performance) is the same. The writer still sees many possible targets worth while for joint efforts between the two countries, but in the course of setting up specific targets we should be careful for the choice; i.e., which ones can bring us the most benefit from joint efforts, and which are not. Not a few research issues are so attached to or bound to individual design and construction practices, which are very different between the two countries, and those may as well be challenged through domestic research efforts.

A few references that describe the damage to steel buildings observed in the 1995 Hyogoken-Nanbu Earthquake follow:

"Preliminary Reconnaissance Report of the 1995 Hyogoken-Nanbu Earthquake," The Architectural Institute of Japan **(AU),** April, 1995, 216 pp.

"Reconnaissance Report on Damage to Steel Building Structures Observed from the 1995 Hyogoken-Nanbu Earthquake," The Steel Committee of Kinki Branch of the Architectural Institute of Japan, 167 pp (in Japanese, attached with an English summary).

Nakashima, **M.,** Inoue, **K.,** and Tada, M., "Classification of Damage to Steel Buildings Observed in the 1995 Hyogoken-Nanbu Earthquake," Engineering Structures, Vol. 20, No. 4-6, April 1998, pp. 271-281.

Nakashima, M., et al., "Full-Scale Test on Beam-Column Subassemblages Having Connection Details of Shop Welding Type," Proc. of the Structural Engineers World Conference, July 18-23, San Francisco, (to appear).

The Effect of Near-Source Ground Motion on Long-Period Base-Isolated Structures

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Introduction

Historically, moderate to large earthquakes have caused significant structural damage in the epicentral regions, but due to inadequate density of strong ground motion sensors in these regions, the detailed nature of these damaging motions remained poorly understood. However, with increasing density of strong motion sensors since the 1970's, a few records began to emerge which revealed not only large peak accelerations, but also large velocities and displacements. The accelerations tended to be in the range that attenuation relationships would predict, but the velocity and displacements were significantly larger than many predicted. These motions also exhibited strong directivity effects. Detailed source modeling by Wald and Heaton(1994) and others resulted in similar patterns for these "long-period" ground motions. This is not unexpected, since increases in peak accelerations tend to be modest with increases in magnitude, but increases in ground velocity and displacements increase dramatically (Boore *et al.,* 1993) which is particularly important for long period structures in the near field (Heaton *et al.,* 1995).

Discussion

Several analyses have been performed on analytical models of base isolated structures. These models include several actual structures in the Los Angeles area. Upon subjecting these models to several of the recorded near-field records, the isolator displacements in some instances exceeded the allotted moat space, indicating the possibility of an impact of the building with the encircling retaining walls.

Therefore, in order to investigate the issue further, a generic base-isolated building model was created and analyzed using the program 2D-BUMP which was written by John Hall (Hall *et al.,* 1995). Subjecting these model buildings to a number of large ground motion records from the Imperial Valley, 1940, the Landers, 1992, and the Northridge, 1994 earthquakes resulted in very large displacements of both the isolators and the superstructure.

Further studies have been recently completed (Halling and Hall, 1997) which have expanded the types of isolators used and has also included several of the ground motion records from the Hyogo-Ken Nanbu (Kobe), 1995 earthquake. All of these analyses were performed using time histories so that the non-linear histories of the structures are visible and meaningful.

Conclusions

Displacements across the isolators was substantial in most cases, often exceeding 30 cm.

In almost all cases the superstructure first story drift exceeded 0.2% indicating that elastic behavior of the superstructure was seldom achieved.

In most cases, the isolated buildings had significantly smaller story drifts than the fixed-base structure, indicating that, if designed for these large displacements, the isolated buildings perform better than a traditionally designed building.

Designing a base-isolated building (or a fixed-based building for that matter) to withstand the Takatori ground motion would be a challenge. If the isolators are designed to control the motions to eliminate impact with the perimeter wall, excessive story drifts in the superstructure occur.

Acknowledgments

The author would like to acknowledge the tremendous contributions of Dr. John Hall to this work. Thanks to Dr. Thomas Heaton and Dr. David Wald for their contributions and their understanding of strong ground motion. Thanks also to Dr. Bill Iwan for providing the opportunity to present this work.

References

Boore, D.M., W.B. Joyner, and T.E. Fumal, Estimation of response spectra and peak accelerations from western North American earthquakes, an interim report, US. *Geological Survey, Open File Report 93-509,* 1993.

Hall, J.F., T.H. Heaton, M.W. Halling, and D.J. Wald, Near-source ground motion and its effects on flexible buildings, *Earthquake Spectra, vol.* 11, no. 4, 569-606, November 1995.

Halling, M.W., and J.F. Hall, Analysis of base-isolated structures utilizing near-source strong ground motions, *Proc. ASCE Structures Congress X-V,* American Society of Civil Engineers, Portland, Oregon, April, 1997.

Heaton, T.H., J.F. Hall, D.J. Wald, and M.W. Halling, Response of high-rise and base-isolated buildings to a hypothetical M_w7.0 blind thrust earthquake, *Science* **267,** 206-211, 13 January 1995.

Wald, D.J., and T.H. Heaton, A dislocation model of the 1994 Northridge earthquake determined from strong ground motions, *U.S. Geological Survey Open File Report 94-*278, 1994.

Developments of Early Earthquake Loss Estimation Systems in Japan

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This paper highlights recent developments of earthquake monitoring and early damage assessment systems in Japan. The first practical idea of real-time seismology may be UrEDAS of the Railway Technical Research Institute [1]. Detecting the arrival of the P-wave by own network at near source, the system estimates the location and magnitude of an earthquake very quickly. Then the system uses this information to stop trains before the arrival of S-wave. The first UrEDAS network started operation in 1989 in Tokyo Metropolitan area.

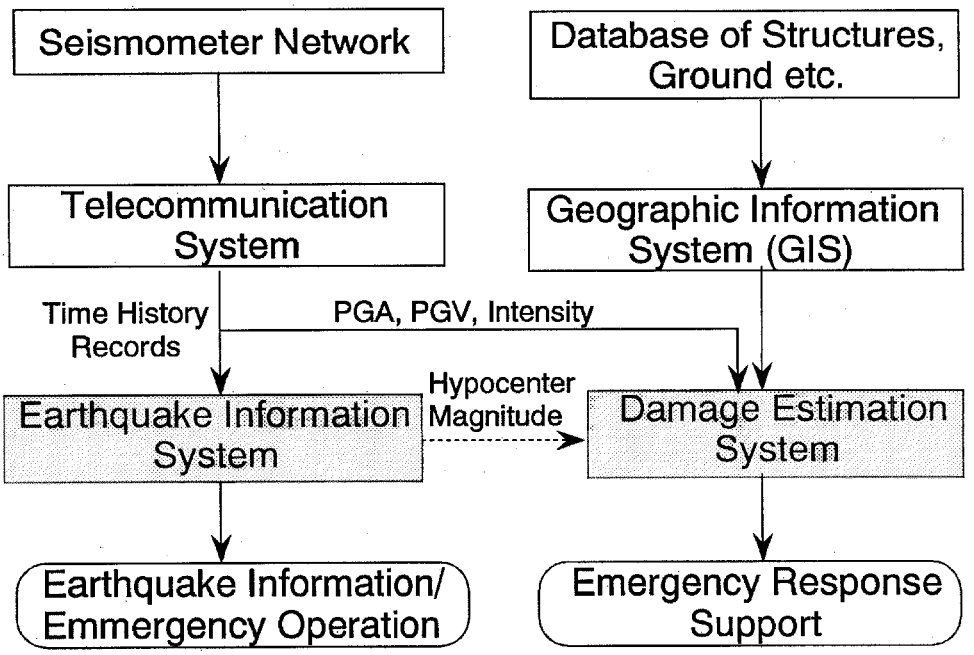
Using the GIS, EPEDAT was developed to estimate building and lifeline damage in the Southern California [2]. Almost at the same time, real-time damage assessment systems were also developed in Japan. SIGNAL of Tokyo Gas Company performs damage estimation of a natural gas network based on extensive earthquake monitoring and GIS [3]. In the system, identification of the magnitude and location of an event is also conducted using data from the own accelerometers and radio network. Kawasaki City and Tokyo Fire Department also developed their own early damage assessment systems for emergency management. These systems in Japan started operation in the early 1994, about a year before the Hyogoken Nanbu (Kobe) Earthquake of January 17, 1995.

After the Kobe Earthquake, earthquake countermeasures have got higher priority than before. Getting new budgets, thousands of strong motion accelerometers will be installed within a few years. In order not to miss localized heavily damaged areas, the number of stations of the JMA was increased to 574. Using records from several stations, the JMA determines the location and magnitude of an event within a few minutes. The Science and Technology Agency also started to deploy a total of 1,000 strong motion accelerometers throughout Japan. The Fire Defense Agency also started a project to deploy one accelerometer for all the municipalities (3,255 in total) in Japan. In addition to these three national networks, many public and private organizations have started or are planning to deploy seismometer networks within their territories.

New early damage assessment systems are also being planned by a number of public and private organizations. As one of such systems, the National Land Agency, which is in charge of disaster prevention administration of Japan, developed an early damage assessment system and started its operation in April, 1996.

Japan had been rather well prepared for earthquake disasters. However, the damage in the Kobe Earthquake was much more than expected and the weakness of crisis management in Japan was revealed. Lessons learned from the earthquake should be used in disaster mitigation. In order to avoid a lack of information just after an earthquake, early damage assessment systems with intensive earthquake monitoring are expected to play a vital role in the near future.

[1] Nakamura, Y. and Ueno, M., "Development of Urgent Earthquake Detection and Alarm system", *Proc. of the 7 Japan Earthquake Engineering Symposium,* 2095-2100, 1986 (in Japanese).
[2] Eguchi, R. et al., "Real-time Earthquake Hazard Assessment in California: the Early Post-earthquake Damage Assessment Tool and the Caltech-USGS Broadcast of Earthquakes", *Proc. of the 5th U.S. National Conf on Earthquake Engineering,* II, 55-63, 1994.
[3] Yamazaki, F., Katayama, T., and Yoshikawa, Y., "On-line Damage Assessment of City Gas Networks Based on Dense Earthquake Monitoring", *Proc. of the 5tli U.S. National Conf. on Earthquake Engineering,* **IV,** 829-837,1994.



Examples:

Japan Rail: *UrEDAS* ---> *HERAS*
Tokyo Gas: *SIGNAL* = *SIGNAL*
California: *CUBE* ---> *EPEDAT*
Nat. Land Agency: JMA ---> *ESS*

Fig. 1 Realtime Eathquake Disaster Mitigation Systems

Development of Smart Structural Systems

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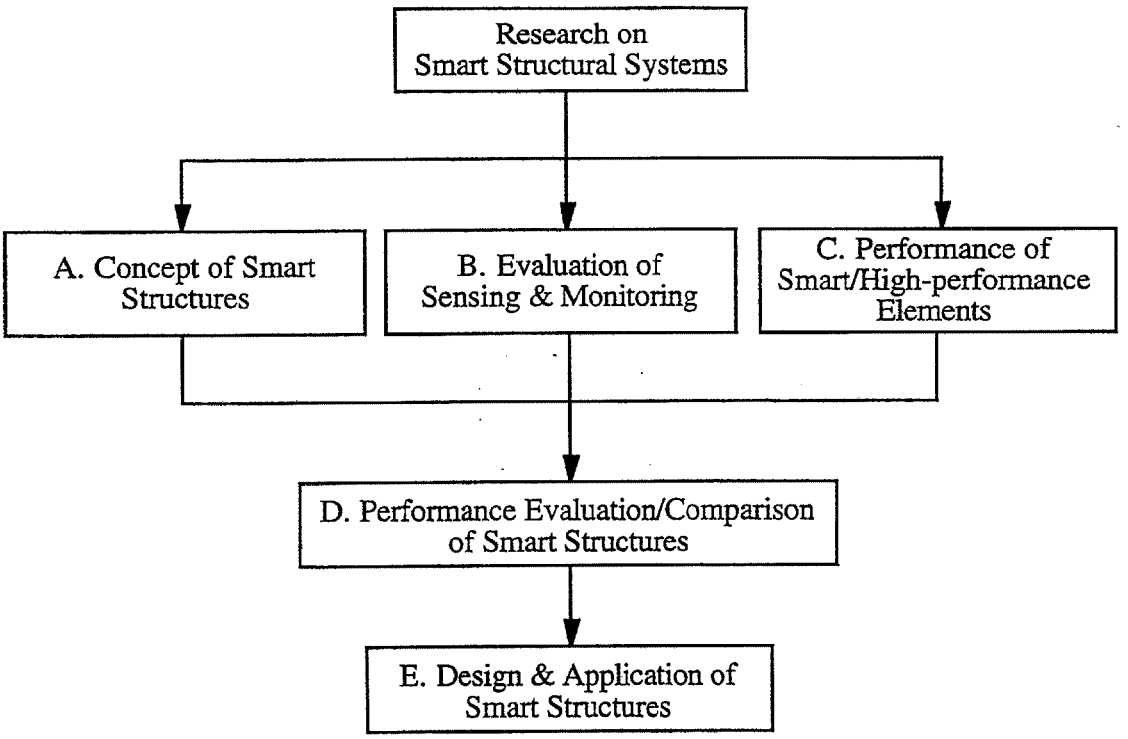
Building Research Institute
Ministry of Construction, Japan

General Research Scheme

Period: Five year project starting in 1998.

To make simultaneous start for both sides of US and Japan, one year planning is scheduled in fiscal year of 1997.



The research subjects for the next term for US and Japan project are to be studied in a dual approach:

- To make structures themselves more highly characterized by using developed technology and knowledge in a SMART way, or by using high-performance materials.
- To make the structural performance higher by using SMART materials/members to structures.

Concept of Smart Structures (98-00)*

The primary objectives are to make performance-enhanced structures by using smart structural design concept. Any materials are applicable. The research objects are

enumerated as follows. The structures of which technology has been well developed are omitted.

Research Subjects are:

- Development of concept of smart structures and smart materials/members
- Structural requirement for performance of smart structures and members
- Feasibility study on smart structures

The concept of smart structures is such as:

- Rocking system
- Structure which utilizes energy dissipation members
- Stiffness-control system

Evaluation of Sensing and Monitoring Technology (98-00)

Research subjects are:

- Evaluation of characteristics of sensing/monitoring and structural identification technology
- Comparison through experimental tests
- Feasibility study on sensing/monitoring and structural identification methods

Sensing materials and instruments are such as:

- Optical fiber
- CFGFRP (carbon-fiber glass-fiber reinforced plastic) material
- Shape-memory alloy
- Piezoelectric material
- Displacement measuring transducer
- Velocity measuring transducer
- Accelerometer

Performance of Smart and High-Performance Structural Elements (98-00)

Research subjects are:

- Evaluation of physical properties of smart materials and members including experimental tests
- Development and evaluation of smart structural members including literature surveillance, tests and analyses

Smart materials are such as:

- Electric/Magnetic rheological fluid
- Shape-memory alloy
- High-performance steel such as low-yield steel
- Piezoelectric actuator
- High-performance concrete
- Self-repairing material
- Composite

Performance Evaluation/Comparison of Smart Structures (00-02)

Research subjects are:

- Development of benchmark programs for buildings, bridges, and other civil infra-structures
- Comparison through the use of standardized analytical and experimental test beds
- Comparison through large-scale structural tests
- Development of structural evaluation methods of smart structures

E. Design Methods and Application of Smart Structures (00-02)

Research subjects are:

- Development of design methods including making easily understandable performance guidelines
- Application to prototype and real structures
- Performance monitoring

*Numerals in ( ) indicate fiscal years.

Development of Performance-Based Structural Design in Japan

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Ministry of Construction, Japan

On February of 1996, it was officially announced by the Ministry of Construction that the Building Standard Law of Japan should be revised into that based on performance. The building code in Japan will be changed from current prescriptive type into performance-based type in a few years. In responding this announcement, the Building Research Institute (BRI) organized the task committee including working groups dealing with structural safety, fire safety, and environmental safety/equipment/living environment. The performance-based building code is now under development at BRI.

In this presentation, the framework and concepts of the performance-based seismic and structural provisions in Japan proposed by BRI is presented. An example of proposed verification procedures against major earthquakes is also given.

Figure 1 shows the conceptual framework of proposed structural provisions. In the principles of structural safety, the required performance and load/force levels are clearly defined. There are four routes in verification methods and associated structural specifications following the principles of structural safety; proposed route, conventional route, small building route requiring no calculation, and other route including alternative verification methods, deemed-to-satisfy provisions, and expert judgments. Seismic effects to buildings are considered on the basis of basic seismic design spectrum defined at the engineering bedrock under surface soil layers.

There are three levels in the objectives and requirements to building structures and load/force/earthquake-motion levels. The objectives are life safety, damage control, and keep of function of a building. The principle of verification methods is that the predicted response values should not exceed the estimated limit values.

The basic concept of BRI proposal for prospective seismic design spectrum is as follows:

1) Basic design spectrum defined at the engineering bedrock

   The engineering bedrock is the soil layer with shear wave velocity of larger than approximately 400 m/s at a site. The spectra with return periods of approximately 500 and 30 to 50 years are used to verify life-safety and damage-control levels, respectively.

2) Evaluation of site response from surface geotechnical data

   The key parameter may be the predominant period of surface soil layers above the engineering bedrock. The nonlinear behavior of soft soil layers is taken into consideration for life-safety verification.

3) Effect of soil-structure interaction

In structural analyses used in verification methods, the effect of soil-structure interaction is considered if necessary, while the fixed-base model of a structure is allowed.

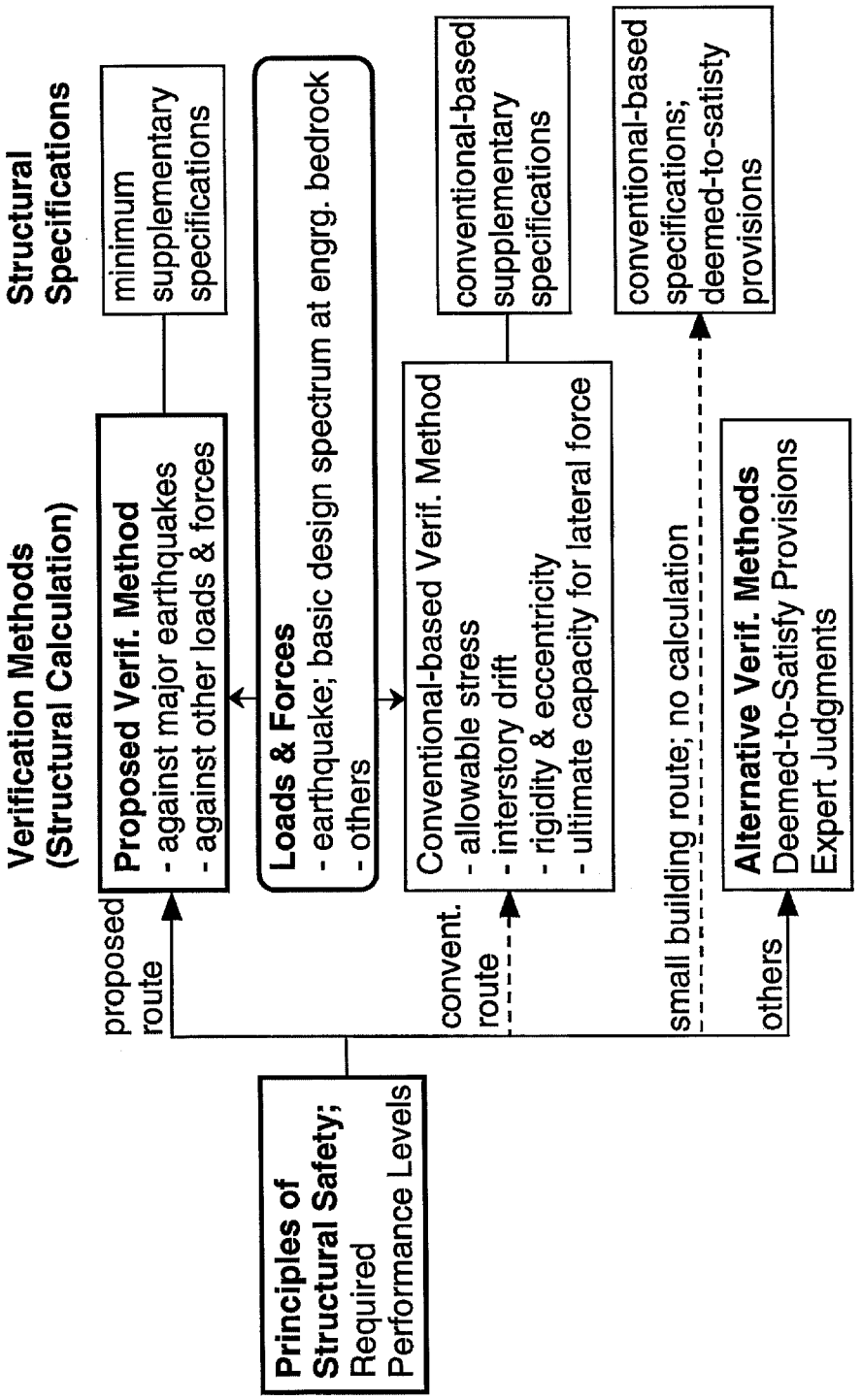

Fig. 1 Conceptual Framework of Seismic and Structural Provisions Proposed by BRI

Fundamental Research for Mitigation of Earthquake Disaster – NCREE Research Progress

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Recognizing the risk of earthquake disaster and learned from the 1994 Northridge and 1995 Kobe earthquakes, the National Center for Research on Earthquake Engineering (NCREE) in Taiwan has recently been equipped with state-of-the-art facilities for earthquake engineering research. The major part of these experimental facilities include a six active degree of freedom earthquake simulator and an L-shape reaction wall. the shaking table has a dimension of 5 in by 5 in which can accommodate a maximum specimen weight of 500 kN. The maximum allowable table displacement, velocity and acceleration are 250 mm, 1000 mm/sec and 3.0 g, respectively. The operating frequency range is from 0. I Hz to 50 Hz. The reaction wall has a total length of 45 meter with variable height ranging from 6 in to 15 in, which is accompanied by a strong floor for quasi-static and pseudo-dynamic tests. Currently, twenty-two high performance servo-hydraulic actuators with loading capacities ranging from 50 kN to 2000 kN, stroke length from 250 mm to 500 mm and servo-valve flow rate of 40 gpm to 400 gpm are available. These advanced experimental facilities allow NCREE to promote its capability for multidisciplinary research and to provide its availability to other scientists and researchers of excellence in earthquake engineering research.

The current research emphases of NCREE encompass:

1. Innovative Technologies for Earthquake Engineering

   (a) Structural Health Monitoring Technology – establish a benchmark model for system identification and damage assessment.
   (b) Active Control Research – different types of controller (such as active bracing system, active mass driver and active tuned mass damper) will be used to verify the control efficiency from different control strategies.
   (c) Passive Control Research – Viscoelastic damper, TADAS, and elastomeric bearing will be tested and design specification for passive control devices will be developed.

2. Seismic Engineering Renewal

Program related to seismic evaluation and retrofit of bridge structures will be conducted **in** the NCREE lab. Methodologies for retrofit of regular bridge column, hollow-section bridge column, column-to-cap beam Joint and column-to footing Joint will be developed.

3. Advanced Building System

(a) Study the dynamic behavior on SRC and RCS **building** system,
(b) Development of composite bridge pier with high ductility,
(c) Pseudo-dynamic testing technology – it will include the development of real-time pseudo-dynamic test and 3-dimensional testing technology,

4. National Program on Natural Hazard Mitigation

Seismic hazard mitigation program is the recent developed national program in Taiwan. For earthquake hazard mitigation program the research works will include hazard potential analysis, risk analysis, earthquake scenario and emergency response. In relating to this program researches will include:

(a) micro-zonation of potential seismic-induced liquefaction of urban cities,
(b) methods to estimate near-field design earthquake motion,
(c) information management for urban earthquake disaster mitigation.

Strength-Reduction Factors for Structures with Triangular Steel Plate Energy Dissipation Device

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In this paper the strength-reduction factors for frame installed with Added Damping and Stiffness device made of triangular plates (TADAS), satisfying predetermined ductility ratio of TADAS device, are investigated using 20 earthquakes recorded in Taipei area and 58 rocksite earthquake records and 58 alluvium-site earthquake records of Taiwan area. Assuming the load-displacement relation of both frame and TADAS device to be bilinear, a trilinear load-displacement relation for the entire system is constructed first. The strength-reduction factors are then computed for a given set of parametric values. In the analysis, the following criteria are adopted: (1) the ductility ratio of frame should not be greater than 2, and (2) the displacement amplification factor should be less than 5.5. For the structural period between 0.5seconds to 5 seconds, the strength-reduction factors for TADAS device with ductility ratio equal to 6 varies from 8.3 and 10.7. A set of formulae, function of structural period and the ratio of initial stiffness of brace members to that of TADAS device, are also proposed.

For economic reasons the current seismic design practice allows structures to undergo controlled local excursions into inelastic behavior without collapse when subjected to strong ground motions. With this design philosophy the design lateral strength in seismic codes is lower, and in some cases much lower, than that required to maintain the structure in the elastic range, since the nonlinear behavior of structure during the earthquake dissipates the input energy, leading to the reduction in the forces exerted in the structure. Currently in designed practice the reduction in forces is determined by multiplying the linear elastic design spectrum by the strength-reduction factor, and only the elastic design is needed. As a result, the strength-reduction factor has been the topic of several studies (Riddell *et al.*, 1989, Miranda, 1993). All these studies indicated that the strength-reduction factor is mainly influenced by the natural period of the system, the maximum tolerable inelastic displacement demand, and the soil conditions at a site.

In recent years the use of energy dissipation devices on structures to reduce the structural responses during earthquakes has been the topic of many research interests, and some devices have already been implemented on real structures. The main philosophy in using energy dissipation device on structures is that the input energy is dissipated by device not by the inelastic behavior of the primary structural members. The prominent advantage of this can be seen from the investigation of damage of structures in recent earthquakes such as Northridge earthquake and Kobe earthquake, indicating that engineers face many difficult situations in repairing the damaged but not collapsed structures. Among many types of energy dissipation device proposed is the one called Added Damping and Stiffness (ADAS) device which can provide both initial elastic stiffness as well as hysteretic energy dissipation to structures (Su *et al.*, 1990, Su, 1992). The ADAS

device is a mechanical device made of steel plates assembled with bolts and/or welds to end block, the top of which is connected to girder while the end block is attached to the brace members. It can be installed at specific locations of either new or existing buildings. As the building sways, the inter-story drift causes the top of the plate to move horizontally relative to the bottom and the energy can be dissipated through the yielding of plates. It has been shown through experimental work that ADAS device can provide a great degree of reliability in the earthquake-resistant design or upgrading of building, and its use would lead to more reliable building performance during severe shaking, if properly designed and implemented. Consequently, it is imperative that the strength reduction factors be developed for each type of energy dissipation device to facilitate the seismic design for structures installed with the same type of energy dissipation device. Therefore, in this study a one-story moment-resisting frame installed with ADAS device made of triangular plates (TADAS) will be considered to compute the corresponding strength reduction factor.

In this paper assuming the load-displacement relation of both the structure and the TADAS device to be bilinear, a trilinear load-displacement relation for the entire system is constructed first. Then, the strength-reduction factors, satisfying predetermined ductility ratio of TADAS device, are computed for a given set of parametric values using 20 earthquakes recorded in Taipei basin and 58 rock-site earthquake records and 58 alluvium-site earthquake records of Taiwan area. In the analysis, the following criteria are adopted: (1) the ductility ratio of frame should not be greater than 2, and the (2) displacement amplification factor should be less than 5.5. The results showed that the strength-reduction factor increase with R_2 no matter what site condition is; however, the values of strength-reduction factors depend on the site conditions. In general, for the structural period between 0.5 seconds to 5 seconds, the strength-reduction factors for TADAS device with ductility ratio equal to 6 varies from 8.3 and 10.7. A set of formulae, function of structural period and the ration of initial stiffness of brace members to that of TADAS device, are also proposed.

The Effect of Strength Deterioration on the Dynamic Response of Simple Systems Subjected to Impulsive Loading

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Introduction

Considerable debate has occurred related to the effect of near-fault ground motions on structural systems. As distinguished from ground motions recorded at moderate distances from the causative fault, these motions contain intense, relatively long duration pulses corresponding to the fault rupture process. Impulsive type motions have various effects on structural systems. To assess the relations among various structural, ground motion characteristics and response, a long term investigation has been initiated. The focus of these studies is to assess the specific effects of various forms of strength deterioration that may occur in steel moment-resisting frames as a result of premature fracture of connections, or more gradual reduction of strength in the inelastic range due to factors such as local and lateral torsional buckling in the plastic hinge regions. Two simple systems are considered to date: a single degree of freedom model, and a one-bay, one-story frame.

Single Degree of Freedom Systems

Four idealized hysteresis models are used for the global response analysis of the structure: (1) Ideal bilinear elasto-plastic [EPP] response, (2) Brittle fracturing response, (3) Gradual reduction of strength from cycle to cycle (isotropic softening), and (4) Negative post-yield tangent stiffness (kinematic softening). Initially, synthetic ground motions that resemble the basic characteristics of fault normal and fault parallel near-field accelerograms are used. A variety of square, triangular and sinusoidal waves are used to develop motions, having different relations among peak values of ground acceleration, velocity and displacement. More than 40 near-fault records are also used.

For the single degree of freedom models, the governing equation of motion is normalized in terms of ductility, normalized displacement, damping, initial structural period, and a factor relating the intensity of the ground motion to the strength of the structure. The ground motions are characterized by the shape of the time history, the peak ground acceleration, velocity or displacement, and various characteristic periods. Structures having different strengths and periods. relative to those used to characterize the ground motion are then analyzed to develop nonlinear response spectra. The analyses consider the four types of hysteresis models mentioned above.

The response of EPP systems is strongly correlated for all types of pulses to structural period and strength. For instance, for motions with a pulse duration longer than the period of the structure, displacement is relatively insensitive to strength, whereas for systems with periods shorter than that of the pulse, inelastic displacements increase disproportionally with reductions in strength. For systems with periods similar to the characteristic period of

the motion, displacements can increase or decrease with reductions in strength. For longer period structures, responses correlate better when ground motions are normalized to have the same peak displacement. As the period of the structure decreases, peak ground velocity and acceleration better characterize the intensity of the motion. The shape of the accelerogram near the beginning of the pulse (the so-called jerk of the motion) has an important effect on motions scaled to have the same velocity.

The effect of strength deterioration is expected to be limited because of the limited cycling possible with simple impulsive loads. However, results (Fig. 1) consistently show that fracture has relatively limited adverse effect, except for short period systems. The effect of fracture seems to be greatest where a large reduction in strength occurs in system that would develop low ductility demand if it responded in an EPP fashion. For weaker systems, expected to develop larger ductilities, the effect of fracture is less severe. Systems with a negative post-yield tangent stiffness are much more strongly affected by impulsive loads. Thus, caution is needed when developing new design details that will avoid fracture, but may have other forms of strength deterioration.

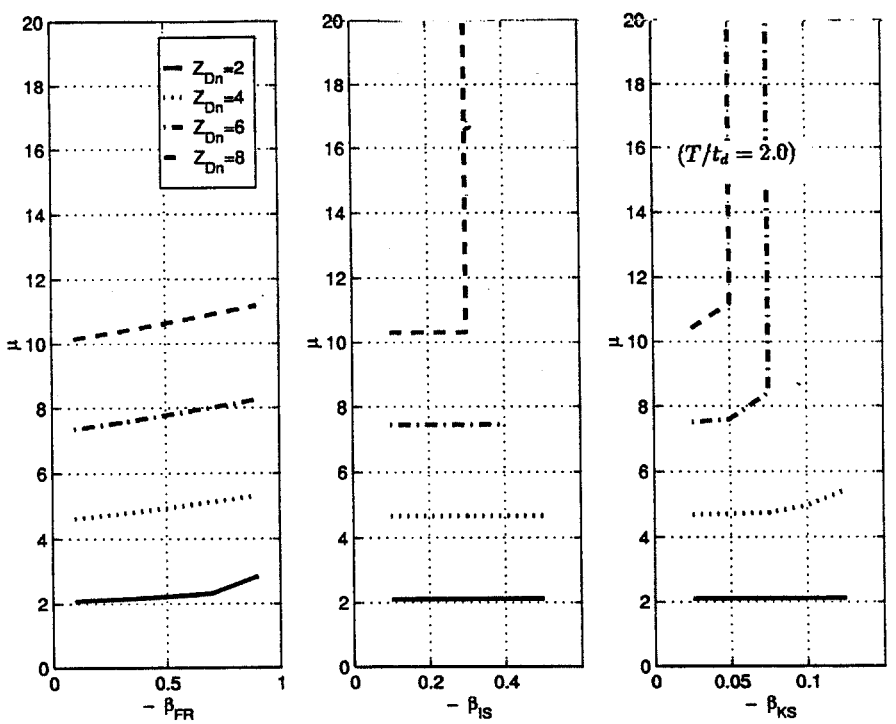
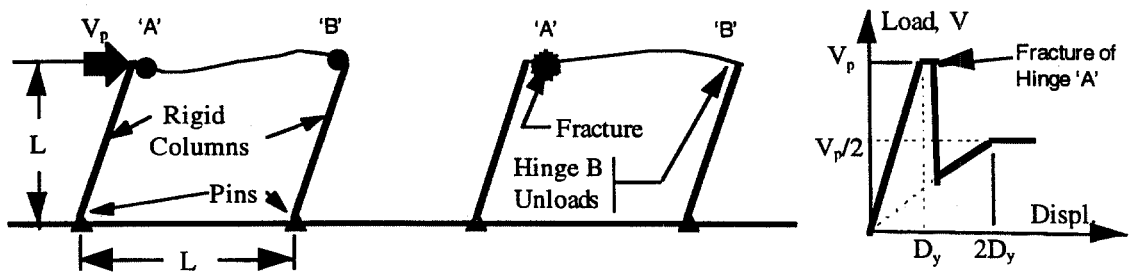


Fig. 1 Effect of Deterioration on Response to Impulsive Loads

Single Story Frames

To assess the effects of the dynamic redistribution of forces that occur in strength deteriorating frames, a simple one story, one bay frame is being studied. For a very simple frame, Fig. 2, the stiffness of the structure decreases by a factor of 4 if the fracture is represented by a hinge. The strength of the structure reduces by a factor of two, doubling the lateral displacement needed to yield the remaining hinge. The "fractured" structure may

have greater displacements due to its longer effective period, the incremental acceleration induced by the sudden reduction in capacity, and the added effects of geometric nonlinearities. However, the extended elastic range may cause many fractured structures to return to the origin after the earthquake.



a. Just after yielding b. Just after fracture with same displacement c. Lateral Load-Displacement

Fig 2 Load Redistribution in a Simple Multi-Degree of Freedom System

Future Work

Current plans are to extend the work to include various types of steel multistory, multiple bay frames. In addition, a shaking table experimental program is under development.

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