OVERVIEW OF A PROGRAM FOR REDUCTION OF EARTHQUAKE HAZARDS IN STEEL FRAME STRUCTURES

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SUMMARY

Considerable research has been conducted worldwide to assess the unexpected damage to welded steel moment frame buildings during the 1989 Loma Prieta, 1994 Northridge and 1995 Hyogo-ken Nanbu earthquakes, as well as to find effective and economical remedies that can be incorporated into analysis, design, and construction practices. A major 5-year program has been undertaken with the sponsorship of the U.S. Federal Emergency Management Agency (FEMA) to synthesize and interpret the results of this research, and to conduct additional investigations to develop reliable, practical and cost effective guidelines for the design and construction of new steel moment-frame structures, as well as for the inspection, evaluation and repair or upgrading of existing ones. Topics investigated as part of this program include (1) performance of steel buildings in past earthquakes, (2) material properties and fracture issues, (3) joining and inspection, (4) connection performance, (5) system performance, (6) performance prediction and evaluation, and (7) social, economic and political impacts. The project utilizes a performance-based engineering framework and addresses issues pertaining to various types of steel moment-resisting frames including those utilizing welded, bolted, and partially restrained connections. The guidelines are applicable to regions of low, medium and high seismicity throughout the U.S.

This paper reviews the overall organization and management of this program of research, guideline development, training and peer evaluation, the scope of the investigations undertaken, and the general organization and contents of the guidelines developed. Companion papers [Malley, 2000; Johnson, 2000; Roeder, 2000; Krawinkler; Hamburger, 2000] in this Theme Session provide added information on the various investigations and guideline provisions.

INTRODUCTION

One of the major overall technical surprises of the Northridge earthquake was the widespread and unanticipated damage to welded steel moment-resisting frame systems. The economy, versatility and presupposed high plastic deformation capacity of welded steel moment-resisting frame (WSMF) buildings has led to their common usage in Los Angeles and elsewhere in the U.S. While no loss of life resulted and none of the shaken WSMF structures collapsed during the Northridge earthquake, a wide spectrum of brittle connection damage did occur. This damage ranged for minor cracking to completely severed beams and columns. Little evidence of ductile yielding prior to fracture was observed. The most commonly observed damage was located in or near the welded joint connecting a girder bottom flange to the supporting column flange; complete brittle fractures occurred in many cases. Damage occurred in new as well as old buildings; in tall as well as in short structures. Damage was observed in commercial, office and residential structures as well as in hospitals and other major public institutions. In some buildings, all of the moment-resisting connections at one or more floors failed, or significant permanent lateral displacements occurred. In a few cases, damage was so severe that buildings were demolished or evacuated following the earthquake.

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While inadequate workmanship was believed to play a major role in the damage observed in some structures, most damaged buildings are believed to have been constructed consistent with the codes and standards of practice in place at the time of the earthquake. The effect of this damage was a general loss of confidence in the procedures used to design and construct welded connections in steel moment frames. As a result, building code provisions were quickly changed to require that new designs be substantiated by testing or test-backed calculations. While addressing the safety of individual structures, such provisions did not provide definitive answers identifying the factors that contributed to this unexpected behavior, and numerous questions remained about the effectiveness of methods to inspect, evaluate and repair WSMF buildings damaged in the Northridge earthquake as well as about the safety of existing WSMF structures that might experience future earthquakes.

PROGRAM TO REDUCE EARTHQUAKE HAZARDS IN STEEL MOMENT FRAME STRUCTURES

Answering these questions involves consideration of many complex technical, professional and economic issues including metallurgy, welding, fracture mechanics, connection behavior, system performance, and practices related to design, fabrication, erection and inspection. Because knowledge in many of these areas was judged inadequate and an systematic approach to finding a solution was deemed necessary, the U.S. Federal Emergency Management Agency initiated a 5-year program to develop and verify reliable and cost-effective methods for the inspection, evaluation, repair, rehabilitation and construction of steel moment-frame structures.

This coordinated, problem-focused program of investigation, guideline development and professional training is managed by the SAC Joint Venture. This joint venture consists of three not-for-profit professional and educational organizations: the Structural Engineers Association of California (SEAOC), Applied Technology Council (ATC) and California Universities for Research in Earthquake Engineering (CUREe). The program is being conducted with the active involvement of engineers, researchers, construction experts and others from throughout the U.S. The Program was conducted into two phases. The second phase is nearing completion.

Phase 1 Activities

The first phase of the Program focused on the development of Interim Guidelines [FEMA, 1995] for the inspection, evaluation, repair, modification and construction of WSMF structures. This phase was supported by limited amounts of testing and other topical investigations. These investigations included a survey of damage to steel frame buildings in the Los Angeles area [SAC, 1997e], detailed dynamic analyses of buildings sustaining moderate amounts of damage [SAC, 1997a], and parametric analytical studies of factors that may have contributed to the observed behavior [SAC, 1997d]. Experimental efforts included ambient vibration tests of damaged buildings, tests of idealized weldments [SAC, 1997b], tests of damaged connections removed from buildings, and tests of full-size beam-to-column connections representative of initially undamaged pre-Northridge details, repaired damaged connections, and upgraded details intended for use in new construction [SAC, 1997c]. Some details of these of these investigations were summarized by Mahin [Mahin, 1999]

The Interim Guidelines [FEMA, 1995] were developed by a committee of ten experts from a variety of disciplines, and extensively reviewed by representatives from engineering practice, building regulatory agencies, the steel and construction industry, financial and insurance institutions, and building owners and managers as well as by various technical experts. The scope of the Interim Guidelines covers welding procedures, quality assurance, post-earthquake actions, and new construction. Specific chapters cover: (a) welding and metallurgy; (b) quality control and assurance; (c) visual inspection; (d) non-destructive testing; (e) classification and implications of damage; (f) post-earthquake evaluation; (g) post-earthquake inspection; (h) post-earthquake repair and modification; and (i) new construction. Two major revisions of these guidelines have been released in Phase 2.

Phase 2 Activities

The second phase of the Program focuses on more detailed, systematic efforts to develop reliable, practical and cost-effective Seismic Design Criteria and standards of practice related to steel moment-resisting frame buildings for:

1. the identification, inspection and rehabilitation of existing buildings prior to a damaging earthquake,
2. the identification, inspection, and repair or upgrading of damaged buildings following an earthquake, and
3. the design and construction of new buildings.

In addition to welded steel moment-resisting frames, the Phase 2 program addresses issues related to partially restrained, bolted and energy dissipative connections. Performance-based engineering formats and procedures have been incorporated as an integral feature of the Phase 2 effort.

The technical approach for the Phase 2 Steel Project is schematically illustrated by Fig. 1. It involves seven basic steps:

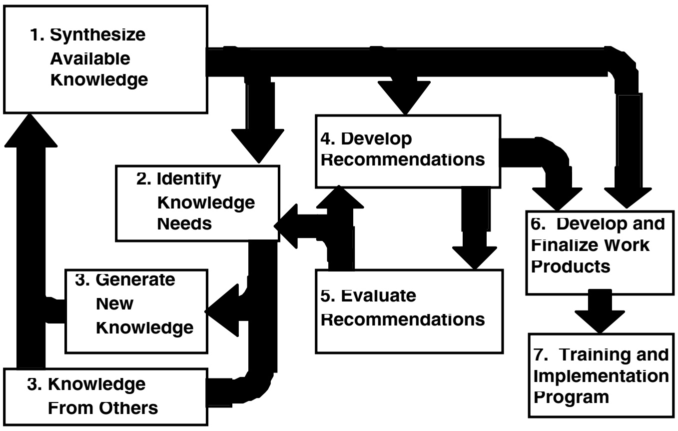

Figure 1 - Conceptual Approach Utilized in Phase 2

1. Synthesize current and new knowledge;
2. Evaluate this knowledge to identify specific information needed to develop and verify the Seismic Design Criteria;
3. Generate the needed knowledge through research, testing and design applications, or through acquisition of research results and other information generated by others;
4. Develop recommendations for inspection, evaluation, repair and rehabilitation of existing steel frame buildings, and for the design and construction of new ones;
5. Evaluate the technical merit and feasibility of these recommendations, including an assessment of their economic and political impacts, through peer assessments, trial designs, physical testing and other means;
6. Develop, review and finalize the Seismic Design Criteria and other documentation; and
7. Implement a knowledge dissemination program.

The intent of this approach is to foster innovation, yet to develop design methodologies and details that are reliable, feasible and economic. This necessitated balanced consideration of the multi-disciplinary technical, professional, economic, social and political issues involved. Care was exercised to coordinate efforts in the Phase 2 Program with other research and guideline development activities in the U.S. and abroad.

A Team-Based Approach Utilized

The Phase 2 program is divided into eleven major tasks spanning over 4 years. The work plan has been developed in conjunction with FEMA and a nationally-representative Project Oversight Committee (POC) consisting of representatives from the design profession, regulatory agencies, and the construction and steel industry as well as experts in public policy and various technical fields. Individual tasks in the Work Plan are related to assessment of current knowledge, conduct of technical and other investigations, synthesis and analysis of the knowledge acquired and its integration into State-of-the-Art Reports, development and review of various design-oriented guideline documents, and implementation of a knowledge dissemination program.

Teams of investigators, technical specialists, and design and construction professionals have been assembled to work on the various investigations, assess social, economic and political impacts, and to develop design guidelines. Technical Advisory Panels have been selected from throughout the U.S. to provide additional expertise and to review the work being carried out by each team. To expedite the work, many tasks have been conducted in parallel and coordinated by the Project Management Committee (PMC) consisting of a Program Manager (S. Mahin), Project Director for Topical Investigations (J. Malley), Project Director for Guideline Development (R. Hamburger), and representatives from three Joint Venture partners (W. Holmes, C. Rojahn and R. Shepherd). To facilitate coordination, leaders for each of the Topical Investigation Teams meet regularly with the six lead guideline writers, PMC, POC and FEMA (M. Mahoney, Program Monitor; R. Hanson, Technical Advisor). Additional information on the make-up of the various project teams and results obtained may be found in the SAC World Wide Web site (http://quiver.eerc.berkeley.edu:8080).

DESCRIPTION OF DESIGN GUIDELINE DOCUMENTS UNDER DEVELOPMENT IN PHASE 2

The Phase 2 steel project culminates in the production of several major deliverables. Design guidelines are applicable to buildings located throughout the U.S. in areas of low, medium and high seismicity. Each of these documents will receive extensive review prior to completion, through focused workshops and solicited written reviews. The guideline documents have been prepared by a team of experts and design professionals. Team members taking the lead in various areas include: J. Hooper, L. Reaveley, T. Sabol, C.M. Saunders, R. Shaw and R. Tide. The major project deliverables include:

1. *Seismic Design Criteria for Steel Moment Frame Construction* – These documents will replace the Interim Guidelines [FEMA, 1995]. Four specific volumes have been formulated to address issues related to: (a) *Seismic Design Criteria for New Moment-Resisting Steel Frame Structures; (b) Evaluation and Upgrade Criteria for Existing Welded Moment-Resisting Steel Frame Structures; (c) Post-Earthquake Evaluation and Upgrade Criteria for Welded Moment-Resisting Steel Frame Structures, and (d) Quality Assurance Guidelines for Steel Frame Construction..* Topics incorporated include: (1) post-earthquake inspection, (2) post-earthquake evaluation, (3) damage repair, (4) evaluation of existing buildings, (5) structural performance levels, (6) base materials and fracture issues, (7) loss estimation, (8) quality assurance and control, (9) structural analysis, (10) seismic upgrade, (11) new building design, (12) connection qualification and design, (13) welding, and (14) structural specifications. [SAC, 1999]

2. *Supplements to the Interim Guidelines* – Improvements are periodically being made to the Interim Guidelines (FEMA, 1995) and published prior to the completion of the Seismic Design Criteria documents (FEMA, 1997c and FEMA, 1999).

3. *State-of-the-Art Reports* – Resource documents have been prepared summarizing knowledge gained during the project related to steel frame design and construction. Separate State-of-the-Art reports are being developed on the following topics: (a) Materials and Fracture; (b) Joining and Inspection; (c) Connection Performance; (d) System Performance; (e) Performance Prediction and Evaluation; and (f) Performance of Steel Buildings in Past Earthquakes.

4. *Report on the Economic, Social and Political Impacts of the Seismic Design Criteria* – The economic, social and political costs and ramifications of implementing the Seismic Design Criteria, and specific means to ameliorate adverse impacts have been assessed and are being described in a report.

PERFORMANCE-BASED ANALYSIS AND EVALUATION APPROACH

A performance-based design, analysis and evaluation framework has been adopted. Two specific performance levels are being addressed – an incipient damage state and a collapse prevention state. A structure that exceeds the limits for the collapse prevention state will experience either local or global collapse. The incipient damage state is a condition in which the structure has experienced no damage and requires neither inspection nor repair. In order to estimate the probability that a structure will exceed the damage limits of desired performance levels within defined levels of confidence, the framework directly accounts for the variability inherent in construction, the randomness of ground shaking hazards, and the uncertainties present in the process of estimating structural response to ground shaking. The reliability-based analysis and evaluation framework developed builds upon a conventional Load and Resistance Factor (LRFD) format. The resulting Demand and Capacity Factor Design (DCFD) framework (see [Hamburger, 2000, SAC, 1999]) differs from the usual LRFD specifications currently incorporated in building codes in that it is based on a probabilistic assessment of the performance of the entire structural system, rather than on the performance of individual building elements, (e.g., beams and columns).

For new construction, the procedures are simplified into a conventional code format, and produce designs consistent with the intent of current building code provisions; i.e., to provide a high level of confidence that designs will be capable of resisting Maximum Considered Earthquake demands with a low probability of collapse. Using the DCFD framework, a designer can consistently and rationally consider other performance objectives, including lower probabilities of collapse, specific probabilities of incurring damage, as well as higher levels of confidence for achieving the target performance levels. For existing structures, the approach provides the basis for assessing likely performance or the confidence that a performance level will be achieved.

TECHNICAL STUDIES UNDERTAKEN DURING PHASE 2

The Work Plan for Phase 2 was developed through efforts of Technical Advisory Panels and the SAC management team, working in conjunction with FEMA and the Project Oversight Committee. To implement the performance-based design, analysis and evaluation approach, information is required on various quantities, including the median levels of expected demand and capacity, their probabilities of exceedence, and the seismicity of the site. To capture this information detailed work statements were developed nearly 100 problem-focused and carefully coordinated studies (see Fig. 2). Brief summaries of these investigation areas are presented below. Additional information on each topic may be found in the companion papers in this Theme Session [Hamburger, 2000; Johnson, 2000; Krawinkler, 2000; Malley, 2000; and Roeder, 2000].

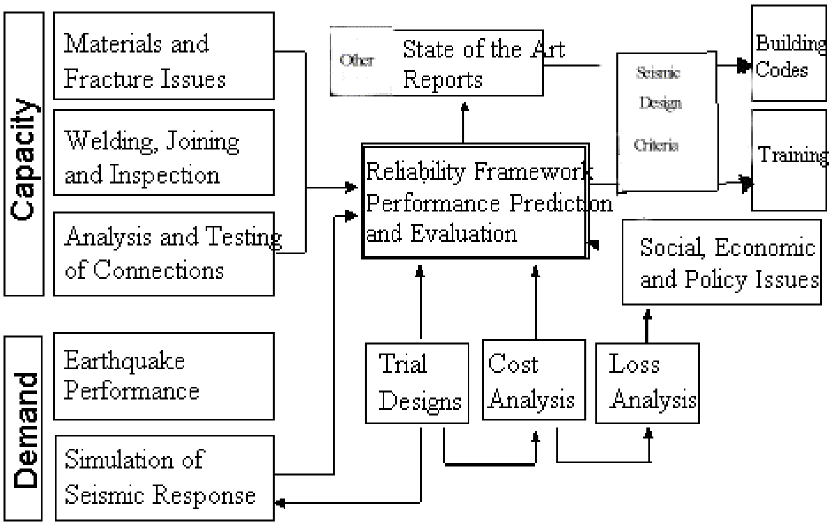

Fig. 2 Schematic Diagram of Activities in Phase 2

Performance Prediction and Evaluation

Using the procedures developed by this team (lead by D. Foutch), guidelines were developed permitting an engineer to determine the probability that either of the two considered performance states will be exceeded by a new or existing structure over a defined number of years, given the seismicity of the site. The team synthesized information from other groups and teams to identify needed information regarding seismicity and capacity. Demand factors were developed to account for differences among response predictions based on various analysis methods (the equivalent static lateral force approach, dynamic linear analyses, and nonlinear static and dynamic analyses) and modeling simplifications. A variety of hypothetical and real buildings has been used to evaluate the methods. The specific investigations undertaken by this team include:

- Develop and implement reliability-based design framework.
- Develop performance-based engineering concepts (demand factors) considering (a) elastic analysis methods; and (b) nonlinear analysis methods;
- Devise design methods for frames needing limited ductility capacity for regions of lower seismicity;
- Assess modeling and evaluation procedures using results from instrumented buildings.

To support this and other system related efforts, three sites were identified across the U.S. representative of high, moderate and low seismicity. Ensembles of ground motion time histories were identified for these sites corresponding to different return intervals (approximately 2500, 475, 72 and 42 years) and representative of firm (and soft) soil conditions. At each site, a series of three, nine and twenty story 'model' buildings were designed according to various criteria (including pre-Northridge and FEMA 267 specifications), and construction costs were estimated for the alternative designs.

Capacity Studies

A series of studies were undertaken to better characterize the capacity of a steel moment-resisting frame building. These investigated the influence of materials, joining conditions and connection details on capacity.

Materials and Fracture

The Materials and Fracture Team examined the material properties (including yield and tensile strength, and notch toughness) of commercially available structural shapes, including new materials just coming on the market. Simple, fracture critical welded joints were also tested to assess the influence of various factors, including the orientation, history and rate of loading, the strength and notch toughness of base materials, joint restraint, and local details. Such studies better identified the loads that could be placed on welded joints. The Team Leader for this research area was K. Frank. Investigations undertaken include:

- Characterize material properties of rolled sections
- Assess through-thickness properties at welded joints between structural sections
- Assess analytical models form material and joint behavior
- Identify desired properties for structural steel and welds

Welding and Nondestructive Testing

To better understand the behavior of welded joints and to develop reliable design criteria, a variety of investigations were undertaken in close coordination with related investigations related to Materials and Fracture and Connection Performance. Tests were conducted on a variety of connections, including standard metallurgical and fracture specimens, complete penetration welds joining wide pull plates, tee-stub joints and full-sized beam-to-column connections. Team leader for this research was M. Johnson. Studies include:

- Evaluate sensitivity of welded joints to different strength base and weld metals;
- Evaluate sensitively of welded joints to different toughness base and weld metals;
- Evaluate sensitivity of welded joints to different temperatures and loading rates;
- Assess sensitivity of welded joints to different weld procedures, parameters and conditions;
- Assess sensitivity of welded joints to heat-affected zone characteristics;
- Evaluate as-built characteristics of weld materials removed from test specimens;
- Evaluate and improve reliability of ultrasonic testing techniques;
- Demonstrate technologies for innovative non-destructive evaluation of in-process construction as well as for post-earthquake damage assessment; and
- Establish weld acceptance criteria based on material properties (strength and toughness), conditions of use (demand), joint geometry and unintended defects.

Connection Performance

Detailed finite element and other analyses have been utilized to identify and assess factors influencing connection behavior, devise methods for predicting the deformation and strength capacities of connections, and to develop simplified analytical methods suitable for design practice. These analyses are closely coordinated with a connection test program. To maximize the utility of the test program, a detailed test and instrumentation protocol was developed. This included loading histories for conventional as well as near-fault ground motions. For welded connections, three general approaches have been followed in developing connection details: (1) improving unreinforced connections, (2) strengthening connections by adding cover plates, ribs or haunches, and (3) locally weakening the beam away from the column face (reduced beam sections). Interior and exterior beam to column connections have been examined, with and without slabs. The effect on behavior of panel zone yielding and local and lateral torsional buckling is being carefully assessed. A variety of bolted connections is also investigated. This research area is coordinated by C. Roeder. Research activities include:

- Detailed fracture-based analyses of various pre-Northridge and "ductile" connections;
- Detailed plastic flow analyses of various new connection details to identify parameters influencing behavior of ductile connections;
- Detailed fracture- and plastic-flow-based analyses of materials, joints and connections to integrate and evaluate analysis methods and interpret test results;
- Develop database and analytically based design methods for welded and bolted connections having different configurations and details;
- Conduct tests and associated analyses of welded connections having:
  - a) Unreinforced connections with improved weld materials, local details, shear tab connections, weld access holes;
  - b) Flange and cover plated connections;
  - c) Reduced beam section details in beams;
  - d) Assess effects of continuity plates;
  - e) Assess effects of weak axis connections;
  - f) Assess effects of column size; and
  - g) Retrofit details.
- Conduct tests and associated analyses of bolted connections having:
  - a) Tee-stub connections;
  - b) Flange plate connections;
  - c) End plate connections;
  - d) Partially restrained connections with clip angle supports; and

e) Simple gravity connections including slab effects.

The results obtained are being summarized along with other tests in a connection test database, and another database is being used to devise and evaluate design methods for estimating connection strength and deformation capacities. Based on an assessment of the results, a series of pre-qualified connection design procedures have been identified for the Seismic Design Criteria documents that will permit design and detailing of connections for routine frame applications without requiring project-specific qualification testing. Each pre-qualification includes the applicable design, detailing, joining and inspection information as well as a statement of the conditions under which the pre-qualification applies. For those applications in which one of the standard connections is not pre-qualified, a project-specific connection qualification procedure has been devised.

Demand Studies

A number of basic studies on the seismic demands on system and connections have been made as a counterpoint to the studies of capacities as influenced by materials, welding, fracture/plasticity and connection geometries. These are based on a review of damages to WSMF buildings during the Northridge, Loma Prieta and other recent earthquakes, and the predicted demands for the 3, 9 and 20 story tall 'model' buildings.

Performance of Steel Frame Buildings during Past Earthquakes

Various investigations are being conducted to assess the performance of steel moment frame buildings in past earthquakes. In addition to the Northridge earthquake, information has been gathered related to the Hyogo-ken Nanbu (Kobe), Landers/Big Bear, Loma Prieta, Whittier Narrows, and other earthquakes. The results have been interpreted to help understand the factors contributing to damage in actual structures, assess recommended damage screening criteria and inspection procedures, identify details and other structural features associated with damage, evaluate the accuracy of analytical methods, and assess the economic, social and other impacts of damage. Two types of simplified evaluation models have been devised from this data: one for estimating structural performance and one for estimating economic losses.

System Performance

Focused investigations were conducted to assess the effect of various structural and ground motion parameters on global and local demands. Model buildings having 3, 9 and 20 stories, located in regions of high, moderate and low seismicity, are used as the basis of these studies. Different computer programs and modeling approaches are being utilized in the analyses. Research in this area is coordinated by H. Krawinkler. The following investigations have been completed:

- Benchmarking of nonlinear dynamic analysis programs;
- Study parametrically the effect on seismic demands of:
    a) Structural configuration, proportioning and modeling;
    b) Deterioration of hysteretic characteristics due to local buckling, brittle fracture, and slip;
    c) Ground motion intensity and dynamic characteristics, including consideration of multi-component excitations and soft soil and near-fault sites;
- Evaluate the safety of steel moment frame systems considering the occurrence of brittle fractures;
- Investigate benefits of alternative framing systems having partially restrained and bolted connections.

ECONOMIC, SOCIAL AND POLITICAL ISSUES

Numerous activities were undertaken to assess the practicability of the Design Criteria and to assess the potential economic, social and political impacts of their implementation (or non-implementation). The Phase 2 activities in this area include:

- Conduct trial applications to assess the practicality and reliability of design and evaluation methods in the Seismic Design Criteria;
- Assess the cost of implementing the Seismic Design Criteria for new and existing structures in terms of initial costs as well as in terms of reduction in damage and losses due to future potential earthquakes; and
- Identify barriers to implementing the Seismic Design Criteria, and assess their economic, social and political costs and ramifications. A report has been published related to this first item [Tobin, 1998].

CONCLUDING REMARKS

New lessons are learned from every major earthquake. The potential for brittle failures in welded steel connections was one of the major unanticipated lessors of the 1994 Northridge earthquake. The FEMA-sponsored program to Reduce Earthquake Hazards in Steel Moment Frame Structures has developed considerable new knowledge illuminating the various factors that interact to control the behavior of these connections, and developed cost-effective and practical guidelines for the design, analysis and construction steel frame buildings containing welded, bolted and other types of moment-resisting connections. A wide array of research has been conducted on subjects ranging from metallurgy to reliability theory and to economic analysis. Based on this and other research, interim and final guidelines have been developed and evaluated. Key to these developments is a reliability-based approach to the analysis and evaluation of systems for specific performance levels. Significantly, the Program has demonstrated the efficacy of problem focused projects that coordinate and integrate research, development, guideline development and training efforts directed at the solution of complex, large-scale technical problems in the field of earthquake loss reduction. The Program has advanced the state of the art in the seismic design of new steel buildings as well as for evaluation and repair or upgrading of existing buildings. None-the-less, numerous technical problems and social, economic and policy issues have been identified requiring further research, development or implementation.

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