

ASSESSMENT OF THE PERFORMANCE OF STEEL MOMENT  
FRAME BUILDINGS DURING THE 1994 NORTHRIDGE EARTHQUAKE:

TASK 3 OF SAC STEEL PROGRAM

Presented by

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INTRODUCTION

Following the January 17, 1994 Northridge earthquake, more than 100 steel buildings with welded moment-resisting frames were found to have experienced beam-to-column connection fractures. The damaged structures cover a wide range of heights ranging from one story to 26 stories; and a wide range of ages spanning from buildings as old as 30 years of age to structures just being erected at the time of the earthquake. The damaged structures are spread over a large geographical area with the highest concentration of reported damage near the epicentral region. Discovery of these extensive connection fractures, often with little associated architectural damage to the buildings, has been very alarming. The discovery has also caused some concern that similar, but undiscovered damage may have occurred in other buildings affected by past earthquakes. Indeed, there have been isolated reports of similar damage having been found in buildings following both the 1971 San Fernando and 1989 Loma Prieta earthquakes.

Welded steel moment frame construction is used commonly throughout the United States and the world, particularly for mid- and high-rise construction. Prior to the Northridge earthquake, this type of construction was considered one of the most seismic-resistant structural systems, due to the fact severe damage to such structures had rarely been reported in past earthquakes, and that only notable collapse of such a structure, the Pino Suarez failure in the 1985 Mexico City earthquake, had ever occurred. That collapse was attributed by investigators to large axial column demands, induced by overly strong bracing in this dual system structure. Subsequent editions of U.S. building codes adopted provisions specifically intended to prevent such failures, and it was presumed by many that buildings designed to these later provisions would be largely collapse resistant. However, the widespread severe structural damage which occurred to such structures calls for re-examination of this premise.

### GOALS AND OBJECTIVES

The Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC) and California Universities for Research in Earthquake Engineering (CUREe) have combined their considerable resources to address and resolve questions relating to the repair, design and retrofit of steel moment frame structures. Their goal for the SAC Steel Program: Reducing Earthquake Hazards in Steel Moment Frame Structures is to:

*Develop professional practices and recommend standards for the repair, design and retrofit of steel moment frame buildings so that they provide reliable, cost-effective seismic performance in future earthquakes.*

Three objectives must be met to achieve this goal:

- 1) Characterize and understand what has happened to steel moment frame buildings in the Northridge earthquake.
- 2) Prepare interim procedures for professional practices and standards:
  - Identify buildings that may have been damaged and require further investigation.
  - Characterize the safety condition of inspected buildings.
  - Rehabilitate damage buildings to provide life-safety.
- 3) Prepare recommendations for the repair, design and retrofit of buildings based on a rational understanding of seismic behavior.

The SAC Steel Program has been specifically designed to achieve this goal in a time frame consistent with the urgency of the problem. Accomplishing these objectives will require marshaling both what is known about the design and seismic performance of steel structures, and what can be learned through directed investigations and analyses to augment existing knowledge. The technical challenges to be overcome are complex and difficult.

The five thousand SEAOC members, the eight major earthquake engineering research universities of CUREe, and the national technical resources of the Applied Technology Council (ATC) are committed to mobilizing all available national and international resources to rapidly and systematically achieve these objectives. Each of these organizations has a history of distinguished achievement. Together they provide a formidable resource for solving this important problem.

## APPROACH

The number and complexity of the technical problems involved, and the importance of the economic and public policy issues raised, suggest that an ad hoc, quick-fix solution is inappropriate and likely to be ineffectual. Indeed, several attempts to date to reach rapid consensus by practicing engineers and researchers have failed - the problems are just too difficult for resolution within the current state of knowledge. A more fundamental investigative approach is needed, one that addresses the full range of associated technical issues and involves the best technical talent and resources available, not only from California, but from throughout U.S.

Restoration of public and professional confidence in the safety and performance of new steel frame buildings and in our ability to evaluate and rehabilitate existing ones requires development and synthesis of knowledge necessary to answer the following simple questions:

- What happened to steel buildings during the Northridge earthquake?
- Why did it happen and can it be predicted?
- How dangerous are damaged structures?
- How can we identify seismically vulnerable structures?
- How can we fix damaged or vulnerable buildings?
- Can this type of damage be avoided in the future?

The SAC Steel Program addresses these questions and will provide answers in the form of recommended standards of practice and draft guidelines. The urgency of these questions and the need for prudent expenditure of funds dictates a short-term program of centrally managed and coordinated investigations.

Achieving the goal and objectives of the project will require a wide array of coordinated individual investigations. These are divided into four basic categories:

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| <b>Category 1</b>  | Immediate investigations to characterize and understand what happened to steel moment frame buildings in the Northridge earthquake.  |
| <b>Category 2:</b> | Other short-term investigations and efforts to develop and peer review interim guidelines for professional practices and standards for identification, evaluation and rehabilitation.  |
| <b>Category 3:</b> | Near-term investigations and analyses to improve understanding of the important factors contributing to the structural performance of steel moment frames and identification of effective and economical methods of evaluation, analysis, design and rehabilitation. |

**Category 4:** Investigations focusing on the refinement, confirmation and assessment practices and standards for evaluation, rehabilitation and design of steel moment frame structures that are identified in Task 2 as reliable and cost-effective.

Phase 1 of the program which is currently in progress, is specifically addressing Categories 1 and 2. Categories 3 and 4 will be the focus of the second phase of the project which will commence later this year. SAC is presently attempting to obtain funding for Phase 2.

### WORK PLAN

The initially formulated Work Plan includes a large number of actions. The following highlights of the draft Work Plan are given to convey the comprehensive set of actions and investigations that were initially perceived as important to achieving the stated goal:

- 1) The immediate focus of the work effort is on near-term needs related to inspection, evaluation and repair of steel frame buildings in Los Angeles and includes:
  - Workshop(s) to refine investigation plans and identify experts and resources interested in participating in program.
  - Detailed field surveys of steel frame buildings in the heavily shaken area.
  - Study of ground motion characteristics and influences on response.
  - Synthesis and assessment of current worldwide states of knowledge and practice.
  - Development and evaluation of interim guidelines for inspection, evaluation and repair.
- 2) Longer range tasks focus on professional practices and recommendation of standards for the repair, design and retrofit of steel moment frame buildings so that they provide reliable, cost-effective seismic performance. These tasks include:
  - Systematically investigate the various technical factors contributing to seismic performance of steel moment-resisting frames, including metallurgy, welding, structural and fracture mechanics, joint design and behavior, structural system behavior, nondestructive evaluation and inspection techniques.
  - Identify effective inspection procedures and nondestructive evaluation tools.

- Develop effective and practical modeling and analysis tools for evaluation of existing steel frames and for the design of new structures.
  - Develop, evaluate and document professional practices and recommendations for design guidelines related to repair, evaluation and retrofit, and new construction.
  - Assess the cost-effectiveness, performance expectations and practicability of resulting guidelines and practices through detailed case studies of public buildings damaged by the Northridge earthquake.
  - Laboratory and field experiments, including large scale component, assemblage and structure tests, will be conducted to gather needed information on performance.
- 3) Implementation of the developed guidelines and standards of practice will be encouraged through frequent workshops and technical bulletins, training materials, instructional programs, and development of electronic data bases.

### **TASK 3 OF THE SAC STEEL PROGRAM**

#### **Detailed Assessment of the Performance of Selected Buildings**

Detailed investigations and analyses (and material and field tests) are being performed on selected buildings to identify the specific causes of failures, to assess the accuracy of available analytical methods, and to identify the conditions under which more severe, life-threatening damage might occur. This activity is building upon previous efforts undertaken by inspectors and engineers following the Northridge earthquake, but is more detailed and focused. Schematic investigations are quantitatively assessing the ability of different types of modeling and analysis procedures to predict dynamic characteristics, and the global and local damage in the building. Also, studies are being undertaken to assess the possible response of the structures considered during hypothetical aftershocks, or other types of future earthquakes to identify conditions that might lead to more severe damage and threaten life-safety. These activities directly support concurrent efforts to develop effective Interim Guidelines and suggest topics for subsequent investigation related to modeling and analysis methods, evaluations procedures, analysis methods, system response and so on.

The overall goals of Task 3 are to:

- 1) identify the specific causes of failure of selected public and private steel frame buildings;
- 2) assess the accuracy of available analytical methods to identify seismic hazards and failure modes;
- 3) identify the conditions under which more severe, life threatening damage might occur; and

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- 4) gather information supporting the development of interim guidelines and standards of practice related to inspection, evaluation, rehabilitation of existing buildings and design of new structures.

This task consists of several inter-related elements:

- 1) Detailed analytical and experimental investigations of specific buildings identifying the reasons for the observed performance, the adequacy of current analytical procedures and modeling assumptions, and implications for inspection, evaluation, rehabilitation, design and construction practices. (Sub-Tasks 3.1 and 3.2)
- 2) Detailed histories and an evaluation of the inspection, evaluation, design, and construction process utilized in one or more buildings. (Sub-Task 3.3)
- 3) A preliminary assessment of the effect of weld and joint fractures on dynamic response and seismic safety. Simple analytical models capable of simulating brittle failures are being developed. (Sub-Task 3.4)
- 4) Preliminary sensitivity studies will be documented and interpreted to assess the importance of:
  - (a) ground motion characteristics (vertical accelerations, near fault effects, bi-directional motions) and structural characteristics (period, irregularity, etc.) on structural performance and
  - (b) the effect of hypothetical aftershocks, or other types of future earthquakes to identify conditions that might lead to more severe damage and threaten life-safety. (Sub-Task 3.5)
- 5) Areas of uncertainty and needed future investigations will be identified.

This paper will address the efforts related to Sub-Task 3.1.

### Sub-Task 3.1: **Detailed Investigations of Particular Buildings**

Detailed investigations and analyses of particular buildings are being carried out to develop an understanding of the reasons for the observed damages and the adequacy of various types of models and analysis procedures to predict the severity and distribution of this damage, both globally and locally. In addition, specific analyses are being carried out to identify the conditions under which more severe, life threatening damage might occur.

A solicitation for proposals to perform these detailed analyses was circulated during December 1994. Over thirty proposals were received for this sub-task, which included more than twenty buildings of interest. The following criteria were used in the selection of buildings to be analyzed in this study:

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- 1) Access to detailed information related to a steel moment frame building which had been severely shaken by the Northridge earthquake, and permission of the owner to participate in this investigation.
- 2) Strong-motion instrumentation within the building, or very near the structure.
- 3) A distribution of building height among the selected buildings was desired (low, medium and high-rise, e.g.).
- 4) A geographic distribution among the selected buildings was desired (San Fernando valley, Santa Monica/West Los Angeles, Santa Clarita, e.g.).
- 5) Different amounts and types of structural and nonstructural damage suffered by the group of selected buildings were desired.
- 6) Demonstrated capability of the proposer in elastic and inelastic analyses of steel moment frame buildings and familiarity with design of such structures.
- 7) Collaboration of practicing engineers and academic researchers.

A total of eight Subcontractors were selected, and nine buildings were included in this study. Included within these nine buildings were structures which addressed a wide variety of parameters and issues, including the following:

- 1) The buildings ranged in height from 2 to 22 stories.
- 2) The complexity of the different buildings ranged from simple, rectangular plans without any irregularities to irregular, complex configurations which included participation by other structural elements (masonry walls, e.g.) at lower levels.
- 3) The majority of the buildings were located in the San Fernando Valley. Buildings located in West Los Angeles and Santa Monica were also analyzed.
- 4) Damage to the different buildings ranged from severe to none at all.
- 5) Varying amounts of frame redundancy were incorporated into different buildings.
- 6) Two buildings on the same site with very different levels were analyzed by two of the subcontractors; one at the Cal State Northridge Campus, and the other at a Woodland Hills medical center.
- 7) Two independent analyses of one building were performed.

- 8) One building in the survey was structurally complete, but the interior nonstructural elements and finishes were not in place, effectively reducing the building mass and damping.
- 9) Three of the buildings have strong motion instruments. One only had a basement instrument. One only had a roof instrument. The third had a series of instruments over the height of the building.

### Analysis Guidelines

The general capabilities of the four different analytical procedures are intended to be assessed as to their ability to predict damage states and susceptibility to increased aftershock damage. These four procedures include the following:

- 1) Equivalent static elastic methods
- 2) Elastic dynamic analysis methods, both response spectrum and time history
- 3) Static nonlinear analyses ("push-over")
- 4) Nonlinear dynamic analysis methods

To insure compatibility of the results obtained by different investigators and to provide a direct means of comparing between different buildings within this sub-Task, a standard set of modeling and analysis standards and a common set of ground motion characteristics (response and time histories) were established for use by all of the Subcontractors. These so-called "baseline" analysis procedures were intended to represent simple analytical approaches which would be commonly used in standard building design (centerline frame dimensions, simple foundation models, no slab or non-frame column participation in lateral resistance, etc.). Baseline assumptions were provided for both the elastic and inelastic analyses. The response spectrum specified was an equal hazard spectrum for the Northern San Fernando Valley, with a recurrence interval of 475 years. Baseline time histories included the following: 1940 El Centro, 1978 Tabas Iran, 1994 Northridge Sylmar County Hospital Record, and the 1994 Canoga Park Record. These records were selected for purposes of comparison to previous standard records (El Centro), representative records from the 1994 Northridge earthquake (Sylmar County Hospital and Canoga Park), and a larger near field event which includes a long duration pulse.

In addition to the baseline analyses, the investigators were encouraged to modify their analytical models to represent more accurate representations of the actual structural systems of the building. These improvements took the form of including the participation of panel zones, composite floor slabs, non-frame columns, foundation flexibility, varying levels of damping, etc. The performance of the enhanced analytical models could then be compared with that of the baseline results. In addition, a simple fracture element was developed as part of Sub-Task 3.4 for use in the nonlinear analyses.

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A suite of simulated time histories were developed for each of the building sites in this Sub-Task which did not have strong motion instruments. These were prepared as a portion of the work in Task 4 of the SAC Steel program. The suite of time histories included nine records for each site. These time histories were developed to provide a mechanism for estimating the demands to which these buildings were subjected as closely as possible.

Various analytical results were collected and evaluated as indicators of damage. For the elastic analyses, these results included the roof displacement ratio, interstory drift ratios, Demand/Capacity ratios (DCR's) for the various members of the frames, etc. For the inelastic analyses, the roof displacement ratio, interstory drift ratios, and inelastic joint and member demands were evaluated. In addition, various investigators attempted to develop other methods for assessing the results.

### Preliminary Assessment of Results

At present, the draft reports for these analyses have been completed and final revisions are being made. While complete analysis of all the data generated by these studies is not yet complete, some preliminary assessments have been performed which have resulted in a number of general observations which will be of use in the development of interim guidelines. Note that these observations were obtained from a review of all of the reports; they should by no means be considered universal, but rather to reflect the preliminary results of this somewhat brief, limited study. A complete analysis of the data and summary report will be developed over the following months, and will be made available with the individual final reports.

The following general trends were identified in these analyses:

- 1) All of the analytical procedures were able in at least a limited fashion to provide an indication of the location of connection damage. That is, analytical indicators could be identified in all cases which were better than random sampling for damaged joint inspection.
- 2) None of the procedures or indicators evaluated were very reliable in predicting specific locations for joint damage. Correlation between joint demand indicators and damage was better if incipient root cracks which were likely present prior to the earthquake were removed from the sample.
- 3) Joint indicators such as DCR or inelastic rotation demand appear to be somewhat more reliable in predicting damage than more global indices such as interstory drift. The postulation of absolute values for DCRs in relation to damage was not possible with the data available.
- 4) Inelastic analyses tend to provide better reliability than elastic analyses in identifying damage patterns. Examples to the contrary were also found in this sample.

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- 5) In taller buildings, higher mode effects appear to have been the cause of a concentration of damage in the upper stories. Push-over analyses can not identify these effects.
- 6) Enhanced analytical procedures beyond the simple baseline assumptions led to improved correlation of damage location and type. Global factors such as interstory drift were not materially affected, but local response predictors were modified. The degree of improvement varied greatly from case to case. Three dimensional effects showed a pronounced improvement for buildings which were susceptible to torsional motions.
- 7) The ground motions generated by the Northridge Earthquake did not generate large interstory drifts, DCRs or inelastic joint rotation demands on the moment frame buildings in this study (maximum drifts on the order of 1.5% or less, DCR with a maximum of 2.5, and joint rotations up to 0.02). Other ground motions considered in the study generated much larger joint demand values and expected interstory drifts.
- 8) Because of time and budgetary constraints, post-fracture analyses were not completed.

### Areas of Needed Future Work

These preliminary observations indicate the need for expanded future efforts with more detailed analytical study and development of procedures and methods which can increase the accuracy of our ability to predict the response and performance of steel moment resisting frames to severe earthquake ground motion. The participation of fracture mechanics concepts in the causes of the connection damage must be better understood, and means to incorporate it into analytical approaches should be developed. Further development of more detailed models of actual buildings should be carried out and compared to building damage. Procedures which can appropriately consider fractured joints must be developed to provide an analytical basis for estimating the reliability of existing steel moment resisting frame structures to provide life safety protection in the event of a future, larger event. Sensitivity studies for various parameters such as ground motions, joint modeling, building configuration, frame redundancy, connection details, etc., should be performed to evaluate design and rehabilitation procedures and building code standards.