SAC
Steel Project

Background Document

Parametric Study on the Effect of Ground Motion Intensity and Dynamic Characteristics on Seismic Demands in Steel Moment Resisting Frames

Report No. SAC/BD-99/01

SAC Joint Venture

A partnership of
Structural Engineers Association of California (SEAOC)
Applied Technology Council (ATC)
California Universities for Research in Earthquake Engineering (CUREe)

By
Gregory A. MacRae
Department of Civil Engineering, University of Washington
Seattle, Washington 98195-2700

Submitted for distribution to
SAC Joint Venture
650-595-1542
http://www.sacsteel.org

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DISCLAIMER

This document is one of a series documenting background information related to Phase II of the FEMA-funded SAC Steel Project. It is being disseminated in the public interest to increase awareness of the many factors which contribute to the seismic performance of steel moment frame structures. The information contained herein is not for design use and is not acceptable to specific building projects. This report has not been reviewed for accuracy, and the SAC Joint Venture has not verified any of the results presented. **No warranty is offered with regard to the recommendations contained herein, by the Federal Emergency Management Agency, the SAC Joint Venture, the individual joint venture partners, or the partner's directors, members or employees. These organizations and their employees do not assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any of the information, products or processes included in this publication. The reader is cautioned to review carefully the material presented herein and exercise independent judgment as to its suitability for application to specific engineering projects.** This publication has been prepared by the SAC Joint Venture with funding provided by the Federal Emergency Management Agency, under contract number EMW-95-C-4770.

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THE SAC JOINT VENTURE

SAC is a joint venture of the Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC), and California Universities for Research in Earthquake Engineering (CUREe), formed specifically to address both immediate and long-term needs related to solving performance problems with welded, steel moment-frame connections discovered following the 1994 Northridge earthquake. SEAOC is a professional organization composed of more than 3,000 practicing structural engineers in California. The volunteer efforts of SEAOC's members on various technical committees have been instrumental in the development of the earthquake design provisions contained in the *Uniform Building Code* and the 1997 *National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions for Seismic Regulations for New Buildings and other Structures*. ATC is a nonprofit corporation founded to develop structural engineering resources and applications to mitigate the effects of natural and other hazards on the built environment. Since its inception in the early 1970s, ATC has developed the technical basis for the current model national seismic design codes for buildings; the *de facto* national standard for postearthquake safety evaluation of buildings; nationally applicable guidelines and procedures for the identification, evaluation, and rehabilitation of seismically hazardous buildings; and other widely used procedures and data to improve structural engineering practice. CUREe is a nonprofit organization formed to promote and conduct research and educational activities related to earthquake hazard mitigation. CUREe's eight institutional members are the California Institute of Technology, Stanford University, the University of California at Berkeley, the University of California at Davis, the University of California at Irvine, the University of California at Los Angeles, the University of California at San Diego, and the University of Southern California. These laboratory, library, computer and faculty resources are among the most extensive in the United States. The SAC Joint Venture allows these three organizations to combine their extensive and unique resources, augmented by subcontractor universities and organizations from across the nation, into an integrated team of practitioners and researchers, uniquely qualified to solve problems related to the seismic performance of steel moment-frame buildings.

ACKNOWLEDGEMENTS

Funding for Phases I and II of the SAC Steel Program to Reduce the Earthquake Hazards of Steel Moment-Frame Structures was principally provided by the Federal Emergency Management Agency, with ten percent of the Phase I program funded by the State of California, Office of Emergency Services. Substantial additional support, in the form of donated materials, services, and data has been provided by a number of individual consulting engineers, inspectors, researchers, fabricators, materials suppliers and industry groups. Special efforts have been made to maintain a liaison with the engineering profession, researchers, the steel industry, fabricators, code-writing organizations and model code groups, building officials, insurance and risk-management groups, and federal and state agencies active in earthquake hazard mitigation efforts. SAC wishes to acknowledge the support and participation of each of the above groups, organizations and individuals. In particular, we wish to acknowledge the contributions provided by the American Institute of Steel Construction, the Lincoln Electric Company, the National Institute of Standards and Technology, the National Science Foundation, and the Structural Shape Producers Council. SAC also takes this opportunity to acknowledge the efforts of the project participants – the managers, investigators, writers, and editorial and production staff – whose work has contributed to the development of these documents. Finally, SAC extends special acknowledgement to Mr. Michael Mahoney, FEMA Project Officer, and Dr. Robert Hanson, FEMA Technical Advisor, for their continued support and contribution to the success of this effort.

PREFACE

The primary objectives of the FEMA/SAC Phase II Steel Project are to develop guidelines for the seismic evaluation, inspection, repair, design and construction of moment-resisting steel frame buildings. A diverse collection of technical investigations is supporting this effort, including the identification of basic material properties in rolled steel sections; development of appropriate welding materials, details, and inspection procedures; specification of anticipated seismic demands imposed on connections as a result of structural response to strong ground motions; and large-scale connection testing to calibrate and verify the design procedures that are ultimately proposed. Tying these activities together is a series of detailed finite element analyses of various connection configurations to quantify the influence of material properties, geometry, and detailing on predicted behavior. In addition, a series of studies have been performed to incorporate the results of the various investigations into a performance-based seismic engineering format that can become the basis of the SAC guidelines. Cost and risk studies and investigations into the past performance of this class of structures were also performed to gather valuable information used in the development of the guidelines and other documents.

This report was carried out as part of the overall efforts of the System Performance team of the SAC Phase II Steel Project. This team was responsible for assessing the likely seismic demands on steel moment frames located in different hazard regions of the US. The team focused primarily on 3, 9 and 20 story steel frame buildings located in Los Angeles, Seattle and Boston (representative of regions of high, moderate and low seismic hazard). Local design professionals designed these structures based on pre-Northridge standards as well as on initial post-Northridge recommendations. System Performance team then carried out a wide range of nonlinear dynamic analyses to assess the sensitivity of seismic response to: the intensity and characteristics of ground motions, fracture of connections, deterioration of the hysteretic characteristics of plastic hinge regions, and the proportions and modeling idealizations utilized. In addition, the team evaluated results of dynamic response of frames incorporating partially restrained connections to assess their applicability to regions of moderate seismic risk. These studies were based on a set of ground motions developed for each city, consistent with current USGS hazard analyses corresponding to 50%, 10% and 2% probability of occurrence in 50 years.

This report focuses on studies undertaken related to the intensity and characteristics of ground motions. In addition to ensembles of ground motion related to different seismic hazard, consideration was given to the effects of near-fault ground motions, multiple components of excitation, and ground motions representative of soft soil sites. This project was performed at the University of Washington in Seattle. This task was identified as Task 5.4.5 of the SAC Phase II program.

Numerous individuals helped to develop the scope and content of this project and to review a preliminary version of this report. These individuals included members of the Technical Advisory Panel (TAP) for System Performance; the Project Management Committee, and several members of the Project Oversight Committee. The contributions of these individuals are greatly appreciated.

ABSTRACT

The effect of ground motion characteristics on the seismic response of steel frames was assessed from inelastic dynamic time-history analysis results of nine two-dimensional frames, and one three-dimensional frame. Frames used in the two-dimensional analyses were seismic frames from 3 story, 9 story and 20 story buildings. Each height of building had been designed assuming it was located in each of Boston, Los Angeles and Seattle. For the three-dimensional analysis, the 3 story frame designed for Los Angeles was used. Ground motion effects were studied using near-fault acceleration records, vertical acceleration records and soft soil records. The effect of the magnitude of ground motion acceleration was investigated by conducting a series of analyses of each 2-D frame using different acceleration magnitudes for the individual records. Also, the effect of the frequency content of the ground acceleration was investigated by modifying the time scale of earthquake records and keeping the magnitude of spectral acceleration at the fundamental period of each 2-D frame constant.

It was found from the 2-D analyses that drifts of the three story structure were approximately linear with height, while the taller structures showed significantly more concentration of displacement in different levels. All structures designed for Boston had sufficient strength to behave elastically.

Near field records representing shaking normal to the strike of the fault (NF-SN records) caused median interstory drifts and inelastic beam rotations in some levels which exceeded 4.5%. Deformation was generally concentrated near the base of the structure. Design level earthquake records, with a probability of exceedance of 10% in 50 years (10in50 records) and near fault strike-parallel (NF-SP records) caused shaking of approximately the same magnitude. However average drifts were generally less than 2.2%. Selected soft soil records caused median peak roof displacements which were generally less than 2.3% and deformation was generally concentrated in the lower stories of the structures. Median residual drifts were approximately 52% of the maximum possible residual drift where the maximum possible residual drift was equal to the peak drift minus the yield drift.

Column moments were up 1.9 times greater, and column shear forces on average 1.6 times greater, than that obtained based on a static inelastic analysis in some stories assuming no strain hardening. The forces were larger due to strain hardening in the beams and dynamic magnification of column forces. Story shear forces were 1.4 times greater than those in the static inelastic analysis.

Vertical ground motions predominantly affected the axial forces in the building columns. The effect of simultaneous horizontal and vertical shaking on the structure, assessed by from horizontal shaking and vertical shaking effects independently, was conservatively predicted by the Sum-of-Absolute-Values (SAV) method. The Square-Root-of-Sum-of Squares (SRSS) method consistently under-predicted the actual response as a result of high axial forces due to horizontal shaking being present in the external columns for relatively long periods of time.

Dynamic push analysis showed that roof displacement did not increase linearly with increasing earthquake acceleration as is commonly assumed by the equal displacement method (EDM). Also records with the same spectral acceleration at the

fundamental period of the structure showed a large amount of scatter in response depending on their frequency content. Peak drifts in the structure initially increased linearly with increasing record intensity. As intensity increased further the peak drift stabilized for a large range of intensity for some records, while for others the peak drifts increased rapidly.

Frequency content analysis showed that even though the structures had the same first mode spectral acceleration for all records, the responses were very different. Records with peak spectral response at periods less than the fundamental period of the structure had peak drifts in the upper stories of the structure. Records with peak spectral response at periods greater than the fundamental period of the structure had peak drifts in the lower stories of the structure.

The seismic response of a near-symmetric three-story steel framed building designed for Los Angeles seismic conditions was assessed using three-dimensional inelastic dynamic time-history analyses with near-fault as well as code design level earthquake records. The 3-D model was different from a 2-D frame model due to the presence of gravity columns modeled with pinned bases, seismic and other perimeter columns modeled with fixed bases, floor stiffness eccentricity, mass eccentricity due to a penthouse, and column biaxial moment and axial force interaction modeled by a fiber hinge. Seismic frames were designed to resist lateral loading in one direction only. It was found that the near field records caused interstory drifts as high as 7% and design level records caused drifts as high as 2%. Drifts from the 3-D frame, subject to strike-normal loading in the plane of the frame and strike-parallel loading in the orthogonal direction, were in some cases greater and in other cases less than in a 2-D frame subjected to strike-normal loading. Torsional effects were small. Standard code rules for bi-directional loading effects in 3-D structures, such as the 30% rule, the 40% rule, SRSS, and sum-of-absolute values (SAV) methods were used to assess the drifts and displacements of the frame. The methods gave different assessments depending on the reference axes chosen. For a reference axes based on the building principal axes, even the SAV prediction underestimated the drift in the first level with some angles of near-fault loading. At this level, orthogonal excitation increased drifts in the main loading direction by up to 100% due to bi-axial yielding at the ground floor seismic columns. For displacement at the top of the building, the SAV assessed the drifts due to NF motions. Gravity columns yielded at the top of the first story columns even though they were pinned at the base. Vertical excitation increased column compressive stresses but did not cause a major detrimental response. Frame pushover analysis generally conservatively predicted beam rotations, however it was not always conservative in the prediction of the column moments or rotations.

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