SAC

Steel Project

Background Document

Performance Prediction and Evaluation of Low Ductility Steel Moment Frames for Seismic Loads

Report No. SAC/BD-00/26

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

Seung-Yul Yun and Douglas A. Foutch

Department of Civil and Environmental Engineering

University of Illinois at Urbana-Champaign

Submitted for distribution to

SAC Joint Venture

650-595-1542

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DISCLAIMER

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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 Performance Prediction and Evaluation team of the SAC Phase II Steel Project. This team was responsible for assessing the ability of various types of analytical models and idealizations to predict seismic response of steel moment frame structures and to recommend appropriate analytical methods for use in design and evaluation. In addition, the team developed a probabilistic approach for assessing the confidence that a structure can achieve a target performance objective (i.e., not to exceed a performance level for a given seismic hazard). Working with Guideline Writers, and based on extensive nonlinear dynamic response simulations, appropriate values for demand and resistance factors were developed along with analysis method and other adjustment factors. The team evaluated the reliability of current code based methods when used in conjunction with SAC prequalified connections.

This report focuses on the seismic performance of ordinary moment frame buildings. Design provisions for these buildings relax some of the requirements imposed on special moment frames; for example, strong column-weak girder provisions, requirements for strength of panel zones, limits for connection deformability, etc. Such structures are possibly suitable for situations where seismic demands are expected to be small, or where lower confidence can be accepted. Recommendations are developed for appropriate demand, resistance and analysis method adjustment factors. This project was performed at the University of Illinois, Urbana. This work was identified as Task 5.5.5 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 Performance Prediction and Evaluation; the Project Management Committee, and several members of the Project Oversight Committee. The contributions of these individuals are greatly appreciated.

EXECUTIVE SUMMARY

Recent earthquakes in Northridge, California and Kobe, Japan have resulted in billions of dollars of damage to buildings, bridges and other structures and the loss of thousands of lives. The suffering of people displaced from their homes and businesses wonder why. Lessons learned from the Michoacan Earthquake in Mexico City in 1985, and from the San Fernando and Loma Prieta Earthquakes that rocked parts of California have been replayed in these recent earthquakes.

A reliability-based, performance-oriented approach has been adopted herein for design and evaluation. This approach was taken in order to account for uncertainties and randomness in seismic demand and capacities in a consistent manner, and to satisfy identifiable performance objectives corresponding to various occupancies, damage states and seismic hazard. Uncertainties due to estimation of period, damping, orientation of the building, live load applied, material property of the components, analysis procedure as well as irregularity of the building are considered. It was found out that the uncertainty associated with the modeling issues as well as irregularity of the building are the major parts. Bias factor which is defined as the ratio of the drift due to nonlinear time history analysis to the drift due to each other analysis method is calculated and tabulated for both new as well as existing buildings. This is based on the assumption that the response from the nonlinear time history is "exact". Therefore additional uncertainty to account for this assumption is applied. Local variability of the slope of the hazard curve, k, was also investigated. According to the study, k for California and Washington was 3.0 and 2.0, respectively. Two stability limits are considered for the capacity determination. One is the global stability limit calculated using the new Incremental Dynamic Analysis (IDA) procedure described in the report. The global capacity of the frame is defined as the drift level at which the increment in drift changes drastically due to an increment in ground motion intensity. The second is the local stability defined as the drift level at which gravity load carrying capacity of the beam is lost. This limit is based on the numerous test results and is different for each connection type. A new aspect of this procedure is that the confidence that the response of the building will not exceed the performance objective may be calculated. Two performance levels are considered: Collapse Prevention and Immediate Occupancy.

For more accurate prediction and evaluation of the performance of the buildings, detailed models were developed that included the contribution from the gravity carrying interior columns as well as composite action from the concrete slab on top of the beams. Tri-linear behavior of the panel zone yielding, strength degrading behavior of the beam-column connection, and yielding behavior of the partial-stiffness and partial-strength connections were also modeled. Expected strength instead of the nominal strength of the material was used to correctly simulate the yielding properties of the structure.

Ordinary Moment Frames (OMF) with Weak-Column Strong-Beam (WCSB) configurations were designed according to the 1997 NEHRP provisions. A 3-, a 9- and a 20-story building for Seismic Design Category (SDC) C was design and analyzed. Since a height limitation of 35 feet was specified for the SDC D, only a 3-story building was considered. For this study, each joint was forced to be WCSB configuration. It was later found that in some cases yielding in some beams in the outside bays occurred. The reason for this was the fluctuation of the column axial forces for the outside columns. As the frame moves to the right, the left-most column goes into tension which changes the column-strength-to-beam-strength ratio. Since there is no requirement on panel zone strength or stiffness for the OMF, in most cases yielding of the panel zone occurred prior to other components. Overstrength ratio which is defined as the ratio of strength of the structure to the design base shear was two when panel zones were allowed to yield whereas the ratio was three when doubler plates were inserted. Guidelines for design and analysis of new ordinary moment frames with weak-column strong-beam configurations are presented. Evaluation and performance prediction of the system is presented based on the findings from the reliability-based performance evaluation method. The 3-story building in Seismic Design Category D for LA did not satisfy the SAC performance objective for IO. The permanent residual drift ratio was 0.0056 compared to the target of 0.005. Therefore, stiffening of the structure is needed. The 20-story building collapsed even with doubler plates were inserted. This collapse phenomenon is due to story mechanism and high P-Δ moments that cause large panel zone plastic rotation for the original structure but large column plastic rotations for the case with doubler plates. This coincides with the poor performance observed from the static pushover analysis. Therefore, it is recommended that the WCSB design is restricted to 120 feet which is equivalent to the 9-story building which met all of the performance objectives. A 99% confidence that the performance objective is not exceeded was observed for all the buildings except for the 20-story building which collapsed. The maximum axial load ratio was also investigated. The maximum axial compression ratio, P/P_{cr}, was observed from the 9-story building which was 0.6. The maximum axial tension ratio, P/P_y, was 0.2. Therefore, the axial loads are within acceptable range.

Other ordinary moment frame systems that consist of Partially Restrained (PR) connections such as T-stub connections, end-plate connections, and clip angle connections are addressed. Stiffness effects and modeling of stiffness for PR connections are also investigated. The study showed that the drift and the beam moment of the frame could adequately be simulated using the commercial structural analysis program by adjusting the bending stiffness of the beam as described in the FEMA 273 document. Ordinary moment frames with different kinds of partially restrained connections are analyzed and compared for their ability to satisfy the performance objectives.

A 3-story building in SDC D and a 9-story building in SDC C was design and analyzed. The 3-story building was mostly governed by drift requirements. Larger member sizes for both columns and beams were used. Therefore, panel zones did not yield at small deformations. The overstrength ratio from the static pushover analysis for 3-story building was three for the case with and without the doubler plates. The 9-story building was governed by drift as well as strength. Therefore, the overstrength values for the 9-story building without and with doubler plates were two and three, respectively. The maximum plastic rotation of 2.5% was observed in the beam connection for the 3-story building whereas 2% was observed in the panel zones for the 9-story building. Axial load ratios as well as performance objectives set for the CP and IO levels were checked. Overall, the buildings with T-stub connections performed well resulting in 99% confidence of satisfying the performance objective.

As was seen from the measured moment-rotation behavior of the connection, the end-plate connection behaves very similar to the fully restrained connections. Therefore, the connection is expected to perform very well based on the SMF studies.

One of the more flexible connections, clip angle connections, were investigated. A 9-story building in SDC C was designed and analyzed. Partial stiffness and partial strength behavior of the connections were incorporated into the model. According to the static pushover analysis results, the strength of the building was comparable with the other 9-story buildings described earlier. However, drastic loss of strength was noticed after reaching 3% of global drift. The overstrength ratio was 2.5. A maximum plastic rotation of 2.2% was observed for the connections whereas 0.9% was observed for the panel zone. The maximum permanent residual drift of 0.64% from the Seattle 50/50 hazard level ground motions revealed that the structure needs to be stiffened. Other than that, the 9-story building in SDC C with clip angles performed well.

Responses of the buildings on soft soil were investigated. Three 9-story buildings, one with WCSB configuration, another with T-stub connections, and one with clip angle connections, were used for the study. Those buildings were excited by the soft soil ground motions of LA and Seattle developed for the SAC project. The maximum median drifts calculated were 1.6%, 1.4% and 1.2% for buildings with WCSB configuration, building with T-stub connections, and buildings with clip angle connections, respectively. Overall, similar magnitude of median responses with larger maximum responses were noticed when compared to the response due to stiff soil ground motions. Therefore, all of the buildings investigated performed well and met all of the performance objectives set forth for this project.

Finally, two probabilistic approaches for evaluating performance of moment frames were investigated. The conventional method shows the fragility in probability of exceeding a limit state for ranges of spectral accelerations while the new method gives the probability of failure. The probability of failure is defined as the probability that the drift demand would be greater than the drift capacity. The advantages of using this method are that the fragility curve can easily be generated and that it can be used to predict the probability of exceeding a limit state for different future earthquake intensity. However, the second method, probabilistic performance curve method, does not show explicitly the failure probability for a future earthquake of different intensity to the given limit state. The new method is able to better estimate the vulnerability of a building since it includes the variability in estimating the limit states as well as the variability of demand responses corresponding to the intensity of the ground motions. The confidence of this method can be further improved by incorporating more acquired information such as uncertainty terms. Both of the methods showed the same trend of the performance of the buildings for each location and soil type. Overall, for the IO level, the building with WCSB configuration was revealed to be the most fragile one and the building with clip angle connection to be the safest one. Local collapse for the CP level always governed for all of the cases. The building with T-stub connections had the highest failure probability except for the LA stiff soil site. The local collapse limit state for the building with WCSB configuration is not defined since the beams do not yield and lose gravity carrying capacity. The building with clip angle connections is the most fragile one for the LA stiff soil site for the CP level.

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