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Phase II of the FEMA/SAC steel project: Development of seismic design criteria and inspection procedures

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Abstract

Welded moment resisting steel frame (WMSF) construction had been the system of choice for major commercial buildings in California for more than twenty-five years. This was largely due to the perceived capability of this system to provide superior earthquake performance as well as the relatively simple task of designing, detailing, and constructing these structures. Following the Northridge earthquake, unanticipated brittle fracture damage was found in a number of these structures. Emergency changes to the Uniform Building Code deleted prescriptive detailing provisions, substituting in their place performance specifications for the design of framing connections. This made design and construction of WMSF structures complex and difficult.

The SAC Joint Venture, a partnership of the Structural Engineers Association of California, the Applied Technology Council, and California Universities for Research in Earthquake Engineering was formed to perform needed research and develop practical design criteria for these structures. In August, 1995, FEMA 267 (SAC, 1995a.) was published, providing criteria for complying with the emergency code change. While FEMA 267 provided much urgently needed information, design of steel frame structures remained a complex task. The SAC Joint Venture is currently engaged in a second phase program of research and development of design and inspection guidelines. Upon completion of this project, circa 1999, the profession will once again have a simplified approach to the design of both welded and bolted moment resisting steel frames (MRSF). These guidelines will incorporate performance-based concepts and provide methods for establishing defined levels of reliability in meeting design objectives.

Introduction

On January 17, 1994, the Northridge earthquake caused over $30 billion of economic loss to the Los Angeles area. The post-Northridge investigation provided many valuable lessons with regard to the efficacy of modern construction practice. Among the most surprising of these lessons was that WMSF construction, previously thought to be highly ductile and capable of surviving very severe levels of ground motion with limited structural damage, was in reality, quite susceptible to the development of brittle fractures under even moderate ground motion intensities.

Prior to this discovery, design of WSMF structures was relatively simple. An elastic static or dynamic analysis was performed to define member forces and frame drifts; beams and columns were proportioned primarily to control drift and to provide for a strong column-weak beam condition, and a standard prescriptive detail was typically specified for connections. Following the discovery of wide-spread damage to WSMF structures, the International Conference of Building Officials adopted an emergency code change, deleting the prescriptive connection detail and replacing it with a performance specification requiring the qualification of connection adequacy through a complex testing procedure. In the wake of the adoption of this emergency code change, engineers were at a loss as to how to design these structures. In February, 1995, SAC published Design Advisory No. 3 (SAC, 1995b.); and in August of that year, FEMA 267 was published. Together these documents provided recommendations for complying with the emergency code change and for designing and constructing WSMF structures capable of more reliable seismic performance.

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While the initial SAC documents provided valuable interim guidance on how to design more reliable steel frame structures, as well information on how to evaluate existing buildings for damage and repair and upgrade of such structures, the procedures contained in the documents remained quite complex and brought forward the requirements to perform qualification testing of connection details proposed for use on projects. The SAC Joint Venture is currently engaged in the second phase of research into the behavior of MRSF structures, and development of engineering and inspection guideline documents. Scheduled for completion in late 1999, these documents will include the following individual publications:

1. Post-Earthquake Guidelines for Welded Moment Resisting Steel Frame Buildings

2. Evaluation and Upgrade Guidelines for Moment Resisting Steel Frame Buildings

3. Design Guidelines for New Moment Resisting Steel Frame Buildings

4. Quality Assurance and Control Guidelines for Steel Frame Construction

In addition to the guideline publications indicated above, a series of State-of-the-Art reports will be prepared containing a summary of the technical basis upon which the guidelines are based. These State-of-the-Art reports will include reports on:

1. Past Performance of Steel Buildings in Earthquakes

2. Materials and Fracture

3. Welding and Inspection

4. Connection Performance

5. Frame Systems Performance

6. Performance Prediction and Evaluation

A final report will provide an evaluation of the social, economic, and political implications of implementation of the new guideline documents. It is hoped that the new guidelines will return the design of moment resisting steel frame structures to a straightforward and simple task, yet providing the reliability in these structures that had previously been incorrectly assumed to exist.

Post-Earthquake Guidelines for Welded Moment Resisting Steel Frames

The Post-Earthquake Guidelines for Welded Moment Resisting Steel Frames publication will provide guidance on when a building should be evaluated for potential post-earthquake damage, how to determine the specific amount of damage a building has experienced, how to assess the importance of this damage with regard to continued use of the building, and how to repair the structure, if necessary.

Following the Northridge earthquake, it was discovered that WSMF buildings may sustain extensive damage with relatively little outward evidence. Previous methodologies that rely on almost exclusively on such evidence, are thus of limited utility for these structures. FEMA 267 provides an alternative, more reliable procedure for post-earthquake assessment of WSMF buildings. It includes a preliminary screening criteria for determining if a structure is likely to have sustained significant structural damage, based on visual assessment, as well as estimates of the severity of ground shaking at the site, and knowledge as to the known extent of damage to neighboring buildings. If the screening evaluation indicates a building has the potential for significant damage, FEMA 267 provides a detailed procedure for determining the extent of this damage and its implications with regard to continued occupancy. These procedures involve the selection of a representative sample of the moment resisting connections in the building, removal of obscuring finishes and fireproofing, and performance of detailed visual and nondestructive evaluation techniques to catalog the extent of any damage.

Each connection is assigned a damage index, indicative of the amount the connection's ability to participate in earthquake load resistance has been degraded. Based on the damage statistics for the sample of connections investigated, a damage index for the entire structure is projected, and the probability that this index exceeds certain trigger levels is estimated. Recommendations for more detailed assessments, or alternatively, decisions to vacate the building, repair, or accept the damage are made based on these statistical estimates.

The post-earthquake assessment procedures contained in FEMA 267, though developed from the available information with broad input from the engineering and research communities, are somewhat controversial. The principal controversy relates to the ability of the sampling procedures to adequately detect the extent of damage in structures and the necessity of performing ultrasonic testing to detect fracture damage. There is mounting evidence to suggest that much of the reported "damage" to WSMF structures following the Northridge earthquake was not damage at all, but rather, pre-existing defects, inclusions, and flaws in the complete joint penetration welds between the beam and column flanges. Under the phase II SAC program additional investigation is being performed to determine if "W1" indications are really damage. In the event that it is conclusively determined that "W1" conditions are not damage, the guidelines may omit requirements for routine post-earthquake UT inspections, greatly decreasing the cost of each inspected connection. If the cost of each inspection can be decreased, the size of the connection sample used to estimate the damage can be increased, improving the reliability of these estimates. The adequacy of the sampling procedures currently in the guidelines is being evaluated though several case studies. In each case study, a building with complete damage inspection data will be subjected to inspections using the sampling procedures contained in FEMA 267. This will permit a judgment to be made as to whether these procedures are adequate. If it is determined that alternate procedures are required to obtain suitable reliability in damage detection, such procedures will be developed and included in the final post-earthquake guideline document.

The FEMA 267 Guidelines discouraged engineers from reinforcing or upgrading connections that were damaged without performing a balanced program of retrofit that addressed the entire structure. This was a result of concern that reinforcement or upgrade of damaged connections, without addressing all connections in a building, could result in the introduction of soft story, weak story, and torsional irregularities in a structure, thereby degrading rather than improving its probable future performance. The result is that most building repair programs conducted to date have been limited to repair of the damaged portion of connection assemblies, using improved welding practice, but without significant reinforcement or strengthening of the individual repaired connections or of the structure as a whole. Structures repaired in this manner probably retain significant vulnerability to damage in future earthquakes. Analytical research performed since the development of FEMA 267 indicates that for most connection reinforcement approaches, no significant increase in irregularity would occur as a result of spot connection reinforcement. Consequently, the SAC Existing Building Guidelines developed in phase II are likely to encourage, rather than discourage, partial upgrades of structures as part of repair programs, in order to obtain at least marginal improvement in future structural performance.

Evaluation and Upgrade Guidelines for Moment Resisting Steel Frame Buildings

The Evaluation and Upgrade Guidelines for Existing Moment-Resisting Steel Frame Structures publication is primarily intended for use by engineers working with existing steel frame buildings that have not yet been damaged by an earthquake. The goal of this document is to enable engineers to evaluate the seismic risk inherent in an existing structure and to provide an upgrade methodology to reduce the assessed risk to user-specified levels.

Seismic risk for a building can be expressed as the probability of experiencing a loss of a given amount, as a result of the building's earthquake performance. Traditionally, seismic risk has most often been viewed in terms of the risk to life safety. However, building owners have also become concerned about potential earthquake induced economic losses. The FEMA 267 document included a loss estimation model for WSMF buildings based on limited actuarial data available in mid-1995. This data consisted of a sample of approximately eighty buildings in the Los Angeles region, for which engineers had voluntarily submitted data on the number and type of connections damaged. Since many of these buildings had not been repaired by the time FEMA 267 was published, losses were estimated based on the number of damaged connections and estimated range of costs to perform repairs. As a result, the loss model contained in FEMA 267 overestimates direct losses as a function of ground motion. Despite the potential inaccuracies in the FEMA 267 loss estimation model, it is the only one available for estimating repair costs in buildings with potential for connection damage. As part of the phase II project, data is being collected on the actual costs incurred in the repair of damaged buildings, allowing the development of a more accurate loss estimation model. This model will be suitable for use by engineers in performing PML (probable maximum loss) studies, often requested by owners acquiring or refinancing a building, based on general data with regard to building size, age, number of stories, regularity, and similar parameters.

The Evaluation and Upgrade Guidelines will also include an Engineering Based model. Since the Northridge earthquake, it has become possible to obtain data on a relatively large range of connection assembly tests, similar to those required by FEMA 267 as part of connection qualification testing. Including data developed by researchers prior to the Northridge earthquake, by SAC and other researchers immediately following the Northridge earthquake, and from project-specific connection qualification tests, there is now a database that includes several hundred connection assembly tests. From this database of test results, it is possible to develop statistical estimates of the plastic rotation capacity of different types of connections, considering such parameters as connection configuration; weld type; beam depth; and relative strengths of beam, panel zone, and column. Taken together with analytical studies of model buildings currently being performed by SAC researchers, a model will be developed to estimate, within a defined level of confidence, the probability of connection damage based on conventional structural analysis approaches. Using currently available data on average building repair cost per damaged connection, it will be possible for engineers to estimate potential building repair costs directly, based on their structural analyses.

Structural analysis in the Existing Building Guidelines will be closely tied to the FEMA 273 (BSSC, 1997a) publication. These include linear static analyses, similar to the equivalent lateral force approach contained in the building codes; linear dynamic analyses; nonlinear static (or pushover method); and a nonlinear dynamic method. FEMA 273 uses these four alternative analytical procedures to estimate the demands on the various elements of a structure. In the linear analysis procedures, these demands are calculated as demand-capacity ratios (DCRs) and in nonlinear procedures, they are calculated as member deformation and force demands. FEMA 273 provides acceptance criteria for three alternative structural performance levels, Immediate Occupancy, Life Safety, and Collapse Prevention. The acceptance criteria are simply limiting values of the DCRs, termed "m values," for the linear procedures, or limiting values for element forces and deformations for nonlinear procedures, for each of the structural performance levels. FEMA 273 is intended to be applicable to all types of structures, including MRSFs.

The SAC Existing Buildings Guidelines will significantly improve upon the acceptance criteria for MRSF structures for the various performance levels currently contained in FEMA 273. In the SAC Existing Building Guidelines, acceptance criteria for the Collapse Prevention level will be based on studies of building behavior, rather than substructure or element behavior. As part of the SAC Phase II research, a number of model buildings have been designed. These buildings are being subjected to an extensive series of nonlinear time history analyses, in order to analytically estimate the ground motion and interstory drift demands that produce analytical predictions of collapse in these structures. These analyses are being performed under a variety of connection assumptions including connections that fracture. Based on these studies, acceptance criteria for the Collapse Prevention performance level will be based on interstory drift demands that produce a statistically defined probability of structural collapse, as opposed to element capacity loss. Interstory drift demand, rather than plastic rotation capacity, will become the primary design parameter used to judge acceptability, greatly simplifying the evaluation process. It is believed that this refinement of the approach taken by FEMA 273 will result in more consistent and less conservative evaluations of building behavior and performance.

FEMA 273 recognizes, even for structures that meet the limitations for linear analysis (low DCR), the distribution of demands predicted by a linear analysis will be less accurate than those predicted by a nonlinear analysis. A somewhat arbitrary 0.75 reduction factor has been added to provide a similar level of reliability in structures evaluated with linear and nonlinear procedures. A similar adjustment factor will be utilized in the SAC Existing Buildings Guidelines, however, it will have an improved analytical basis. As part of the previously discussed studies, the same model buildings are being analyzed to compare the predicted interstory drift demands with those obtained from the nonlinear time history analyses. Based on these differences, bias correction factors will be selected for each analysis type. It is anticipated that nonlinear dynamic analysis would have a bias correction factor of unity, while each of the other analysis methods would have a larger correction factor, increasing the calculated demands, based on the reliability of the analytical approach. Essentially, this bias correction factor may be thought of as type of load factor, as used in LRFD design procedures.

FEMA 267 suggests that upgrade designs may be performed by reinforcing existing individual connections or by modifying the existing lateral force-resisting system such that demands on the existing connections are reduced to acceptable levels. This basic philosophy will be retained in the SAC Existing Buildings Guidelines. Methodologies for predicting connection demand, given the addition of braced frames, shear walls, energy dissipation systems, and other supplemental lateral force-resisting elements will be based on the FEMA 273 methods, modified as discussed above. However, extensive additional acceptance criteria for various existing and reinforced connection types considering beam depth, steel grade, and weld joint type and material, will be provided, based on the testing currently being conducted by SAC, NIST, NSF, and other research organizations. An extensive number of tests of typical pre-Northridge connections and connections with improved welding procedures are being performed to better define the capacity of these connections.

Design Guidelines for New Moment Resisting Steel Frame Buildings

The Design Guidelines for New Moment Resisting Steel Frame Buildings are intended to restore a condition that allows prequalified connections, ending the requirement to perform, or at least obtain, qualification test data for a connection detail prior to using it on a project. It is anticipated that the New Building Design Guidelines will include prequalification data on a number of alternative connection types including reduced beam section (RBS) connections; cover-plated connections; haunched connections; improved bolted-web, welded flange connections; bolted connections, proprietary connections, and other connection types. The prequalification that existed in the Uniform Building Code for bolted-web, welded-flange connections prior to the Northridge earthquake was unrestricted with regard to its application. It has been conjectured that one of the reasons this connection was not successful was that it was routinely applied for use in connecting member sizes for which it had never been tested or evaluated. The prequalifications contained in the New Building Design Guidelines will explicitly indicate the range of member sizes and the structural demands for which these connections are prequalified. Connection specific welding and inspection criteria will also be provided. In addition, connection design procedures used to determine the thickness and length of plates, haunches, and weldments; section reduction parameters; number of bolts, and similar details will be provided for each connection prequalification.

The New Building Guidelines will be compatible with the model adopted by the 1997 AISC Seismic Provisions (AISC, 1997) and the 1997 NEHRP Provisions (BSSC, 1997b), upon which the 2000 International Building Code will be based. Under these Guidelines, MRSFs can be designed as Special Moment Frames (SMFs), Intermediate Moment Frames (IMFs) or Ordinary Moment Frames (OMFs). R values and height limitations are assigned to each of these systems. Regardless of the system selected, the NEHRP Provisions imply that structures designed to meet the requirements of the Provisions will be capable of meeting the Collapse Prevention performance level for a Maximum Considered Earthquake (MCE) ground motion level and to provide Life-Safe performance for Design Basis Earthquake (DBE) ground motion that has 2/3 of the severity of the MCE ground motion. The acceptance criteria (R values and drift limits) contained in the Provisions are based on historical precedent more than analytical demonstration. However, as previously described, the SAC Phase II research program includes an extensive series of investigations intended to determine the design margins provided at various interstory drift limits, as well as the actual drift demands produced in structures designed in conformance with current code. This will enable judgments on the performance reliability provided by the NEHRP Guidelines and adjust the design acceptance criteria as needed to obtain a suitable level of reliability. The SAC New Building Design Guidelines may adjust the R values and drift limits for the various structural systems, and/or adjust the connection rotation capacity requirements in order to provide the intended performance.

Many of the requirements contained in the SAC New Buildings Guidelines will be similar or identical to those contained in the relevant NEHRP, AISC, and AWS provisions and code documents. Rather than reprinting each of these documents, the SAC Guidelines will adopt their provisions by reference, modifying them as appropriate. The New Building Guidelines will use the same analytical procedures as the Existing Building Guidelines and will similarly employ bias correction factors in order to ensure that the demands predicted by the various procedures are suitably accurate. Since FEMA 273 already provides extensive documentation on these analytical methods, the SAC Guidelines will adopt the FEMA 273 methodologies by reference, but also provide more specific guidance on modeling of steel structures, and appropriate values for various design coefficients than is currently contained in FEMA 273.

Regardless of the adequacy of design provisions and approaches, the reliability with which buildings will actually be able to attain their design performance objectives is largely dependant on the conformance of the actual construction with the design intent. The Northridge earthquake clearly demonstrated that construction quality is often significantly poorer than intended in the design, and the engineer is often uncertain how this can be improved. Therefore, in addition to design criteria, the New Building Design Guidelines will also provide recommendations for design and construction quality assurance programs for new building construction. It will also include recommendations for project specifications.

Quality Assurance and Control Guidelines for Steel Frame Construction

Many engineers currently have little understanding as to the actions that should be taken to help ensure that their designs are constructed as anticipated. This problem cuts across all phases of engineering practice including repair and upgrade of existing structures as well as construction of new buildings. The SAC Quality Assurance and Control Guidelines for Steel Frame Construction will provide a ready reference for engineers on this subject. The Quality Assurance Guidelines will include specific information that should be specified by engineers in their construction documents as to the necessary qualifications of quality control and quality assurance personnel; the responsibility of the contractor, special inspector, and building official in the quality assurance and quality control process; the specific tests and inspections that should be performed by each; the observations and inspections that the engineer should perform; and the acceptance criteria for each of these various tests and inspections.

Many engineers often specify that Special Inspection to be provided on their projects, without complete understanding of the available specific tests and inspections or the limitations and benefits of each of these methods. The actual requirements for performing inspections of steel construction are located in a number of standard specification documents, codes, and individual supplier catalog data sheets. The SAC Guidelines will provide a reference for field construction and inspection personnel of the pertinent quality control and quality assurance material contained in these documents, including appropriate acceptance criteria and reporting forms. The Quality Assurance Guidelines will include specific information in this regard to assist the engineer in defining appropriate quality control and quality assurance programs, in monitoring the conduct of these programs, and in evaluating the inspection and test reports.

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