Update on the AISC Seismic Provisions

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HISTORY OF SEISMIC CODE DEVELOPMENT FOR STEEL BUILDINGS AND THE 1994 NORTHRIDGE EARTHQUAKE

Between the advent of incorporating seismic design provisions into the Uniform Building Code (UBC) in the early 1950s, and the late 1980s, the Structural Engineers Association of California (SEAOC) Seismology Committee was almost completely responsible for the content of these provisions. Spurred on by the federally funded National Earthquake Hazard Reduction Program (NEHRP), in the late 1980s and early 1990s seismic design began to be seen as more of a nationwide issue. During these years, the NEHRP program began to fund the Building Seismic Safety Council (BSSC) to develop model building code provisions for seismic design. The BSSC established a nationally represented committee structure, with technical subcommittees addressing each of the main structural materials, including structural steel. To support this effort, the American Institute of Steel Construction (AISC) established a parallel committee (TC 9) and began the development of a set of seismic design provisions for steel buildings. These provisions, first published in 1992, under the direction of committee chair Professor Egor Popov, had scope and content similar to the SEAOC developed UBC provisions, but were developed in the LRFD format rather than ASD. Since the entire 1994 NEHRP Provisions (FEMA, 1994) document was based on a strength design basis, the BSSC TS 6 subcommittee on steel structures adopted the 1992 AISC Provisions (AISC, 1992) by reference with minor modifications.

With the damage to steel buildings caused by the 1994 Northridge earthquake, there was a significant increase in the effort required to update the seismic design provisions. Since there was significant overlap in the scope and membership of the BSSC TS6 and AISC TC 9 committees on seismic design, it was decided that these two committees should work in concert to develop the next edition of the AISC Seismic Provisions. The committees met jointly on numerous occasions in 1995 and 1996 with publication of the provisions in 1997 (AISC, 1997). As a result of this joint effort, these provisions were adopted by reference in the 1997 NEHRP Provisions (FEMA, 1997a), without modification.

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THE FEMA/SAC PROJECT

As a result of the damage suffered by steel moment frame buildings in the Northridge earthquake, there was unprecedented research to understand the reasons for the damage and to develop new code recommendations intended to improve future seismic performance of steel buildings. A six-year program sponsored by the U.S. Federal Emergency Management Agency (FEMA), synthesized and interpreted the results of this research, and conducted 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. This program was completed for FEMA by the SAC Joint Venture, a joint venture of SEAOC, the Applied Technology Council (ATC), and the Consortium of Universities for Research in Earthquake Engineering (CUREe).

The first phase of the FEMA/SAC project was a one year effort intended to provide information to the engineering community in a rapid manner. This phase culminated with the publication of FEMA 267 (FEMA, 1995) and 267A (FEMA, 1997b) Interim Guidelines. These guidelines provided engineers with recommendations for the inspection, evaluation, repair, rehabilitation and design of steel moment frame buildings. For the design of new buildings, the guidelines provide extensive recommendations that address many of the concerns related to the Northridge damage. Items such as the improved understanding of the material properties of base and weld filler metals needed for improved seismic performance led to recommendations for demonstrating minimum toughness in both materials. In addition, the concept of moment connection design changed to move the location of inelastic action into the steel beam and away from the welded joints. This fundamental change is intended to protect these joints from the type of fracture that occurred in the Northridge earthquake. A series of promising connection design options were included in the guidelines to assist the engineer in the selection of appropriate solutions for their specific design applications.

The second phase of the FEMA/SAC program built upon findings from the Phase 1 and other investigations, and undertook a variety of research and professional activities necessary to more fully achieve the objectives of the program. The specific objectives identified for the Phase 2 program were to develop reliable, practical and cost-effective guidelines and standards of practice for steel moment frame buildings related to:

- the design and construction of new buildings,
- the identification, inspection and rehabilitation of existing at-risk buildings prior to a damaging earthquake, and
- the identification, inspection, and repair or upgrading of damaged buildings following an earthquake

The Phase 2 steel project culminated late in 2001 with the publication of design guidelines applicable to steel moment frame buildings located throughout the U.S. The major project recommendations, along with explanatory commentary, are contained in:

- FEMA 350—*Recommended Seismic Design Criteria for New Steel Moment Frame Buildings*. This publication provides recommended criteria for the design of new steel moment frame buildings to resist the effects of earthquakes (FEMA, 2000a).
- FEMA 351—*Recommended Seismic Evaluation and Upgrade Criteria for Existing Welded Steel Moment Frame Buildings*. This publication provides recommended methods to evaluate the probable performance of existing steel moment-frame buildings in future earthquakes and to retrofit these buildings for improved performance (FEMA, 2000b).
- FEMA 352—*Recommended Postearthquake Evaluation and Repair Criteria for Welded, Steel Moment Frame Buildings*. This publication provides recommendations for performing post-earthquake inspections to detect damage in steel moment-frame buildings following an earthquake, evaluating the damaged buildings to determine their safety in the post-earthquake environment, and repairing damaged buildings (FEMA, 2000c).
- FEMA 353—*Recommended Specifications and Quality Assurance Guidelines for Steel Moment Frame Construction for Seismic Applications*. This publication provides recommended supplemental specifications and recommended procedures to ensure that steel moment frames are constructed with sufficient construction quality to perform as intended when subjected to severe earthquake loading (FEMA, 2000d).

Detailed derivations and explanations of the basis for these design and evaluation recommendations may be found in a series of state of the art reports. These reports include:

- FEMA 355A—S*tate of the Art Report on Base Metals and Fracture* (FEMA, 2000e)
- FEMA 355B—*State of the Art Report on Welding and Inspection* (FEMA, 2000f).
- FEMA 355C—*State of the Art Report on Systems Performance* (FEMA, 2000g).
- FEMA 355D—*State of the Art Report on Connection Performance* (FEMA, 2000h).
- FEMA 355E—*State of the Art Report on Past Performance of Steel Moment-Frame Buildings in Earthquakes* (FEMA, 2000i).
- FEMA 355F—*State of the Art Report on Performance Prediction and Evaluation* (FEMA, 2000j).

In addition to the recommended design criteria and the State of the Art Reports, technical reports for each of the over sixty investigations were prepared to document the analytical and experimental studies completed as part of the program.

THE 1997 AISC SEISMIC PROVISIONS

The 1997 AISC Seismic Provisions for Structural Steel Buildings (AISC, 1997), published on April 15, 1997, incorporated many of the early advances achieved as part of the FEMA/SAC program and other investigations and developments related to the seismic design of steel buildings. Part I of these provisions, in Load and Resistance Factor Design (LRFD) format, updated design requirements for materials, welded and bolted joints, and columns and column splices that apply to all structural systems. System specific new requirements are also provided for each different structural system. Three new systems, Intermediate Moment Frames (IMF), Special Truss Moment Frames (STMF) and Special Concentrically Braced Frames (SCBF) were introduced in the 1997 Provisions. A major expansion to the quality assurance requirements for the seismic system is also included. Finally, an appendix for the testing of steel moment resisting connections was developed to assist engineers engaged in project specific testing. Part II of the provisions addresses the design and construction of composite steel and reinforced concrete. Part III of the Provisions mimics Part I, but was written in an Allowable Stress Design (ASD) format. This part was included in the provisions to ease the transition from working stress to strength seismic design of steel structures. Part I of the 1997 AISC Seismic Provisions were incorporated into the 2000 IBC (ICC, 2000) by reference. Some specific elements of the 1997 provisions included the following:

- Added ASTM A913 steel as an acceptable material. This steel is a quenched and self-tempered product that brought 65 ksi material to the structural market.
- Specifies system overstrength factors.
- Recognizes variations between minimum yield strength and expected yield strength of different materials. This recognition is important for situations where the provisions require comparison of member strengths to control the location of inelastic deformations.

- Provides requirements for the design of bolted joints. Specifies that load may not be shared between welds and bolts in the same line of action.

- Requires that all complete-joint-penetration groove (CJP) welds in the seismic system be made with materials that have a required Charpy V-notch toughness of 20 ft-lb at -20 ºF.

- Requires demonstrated base material Charpy V-notch toughness of 20 ft-lb at 70 ºF.

- Increases the design loads to be used in the design of column splices.

- Requires demonstrating moment connection rotation capacity via full scale tests.

- Clarifies that the AISC Seismic Provisions must be followed for all buildings designed with an *R* factor greater than 3. The complementary statement is that when allowed by model building codes (typically for the lower Seismic Design Categories), seismic force resisting systems may be designed using the AISC LRFD Specification (AISC, 1999a) using an *R* factor of 3 or less.

Supplement No. 1 to the AISC Seismic Provisions

Recognizing that rapid and significant changes in the knowledge base were occurring for the seismic design of steel buildings, especially moment frames, the AISC Committee on Specifications committed to generating frequent supplements to the Seismic Provisions. This commitment was intended to keep the provisions as current as possible. The first such supplement was completed and published on February 15, 1999. Supplement No. 1 to the 1997 AISC Seismic Provisions (AISC, 1999b) included the following major items:

- Added ASTM A992 steel as an acceptable material for rolled shapes. This material specification was developed to respond to concerns regarding the maximum yield stress and yield-to-tensile ratio of rolled shape products. A992 has replaced ASTM A572, Grade 50 as the primary product used for rolled structural shapes on the U.S. market.

- Required that all welds in the seismic force resisting system be made with notch tough welds as specified in the 1997 Provisions.

- Highlighted the potential problems with low toughness materials in the "k" area of rolled shapes.

- Recognized the test loading protocol developed for the FEMA/SAC program.

- Clarified the configuration of gusset plate details in SCBF frames.

Supplement No. 2 to the AISC Seismic Provisions

Supplement Number 2 to the 1997 AISC Seismic Provisions (AISC, 2000) was published on November 11, 2000. This supplement continued AISC's attempt to keep the seismic specifications as current as possible. Supplement No. 2 specifically attempted to incorporate a number of the final recommendations that were generated by the FEMA/SAC Project. These changes included the following:

- Added requirements to avoid material discontinuities created by fabrication or erection errors, the placement of welded shear studs or the attachment of other construction in the plastic hinging zone. This change was made in recognition that such discontinuities in these critical zones can lead to premature fracture.

- Changed connection test acceptance criteria from inelastic rotation to interstory drift angle. Modified the testing appendix to follow a consistent approach.

- Revised the requirements for panel zone shear strength in Special Moment Frames (SMF), such that excessively weak panel zones would be avoided. Tightened the column width-thickness ratio and lateral bracing requirements for conditions where column inelasticity is a possibility. This criteria recognizes that limited column hinging can not be precluded for moment frames unless the columns are significantly stronger (on the order of twice) the beams.

- Redefined Intermediate Moment Frame (IMF) systems to be more consistent with the tested connection system previously defined as part of Ordinary Moment Frames (OMF). Limitations on usage are defined in the 2000 NEHRP Provisions.

- Redefined OMF systems as the untested portion of the previous definition, with even more severe application limitations.

In addition the limitations on the use of Ordinary Concentrically Braced Frames were also made stricter, reflecting the limited ductility of this system. Consistent changes were also made to Part II of the document. Commentary changes were made to be consistent with the proposed changes. In addition, other sections of the Commentary were improved.

THE 2002 AISC SEISMIC PROVISIONS

The most recent set of modifications to the 1997 AISC Seismic Provisions was recently completed in 2002 and published in 2003. Because the scope of changes that have been made to these provisions since 1997 has been so large, the provisions have been republished in their entirety. The 2002 edition of the AISC Seismic Provisions continued to incorporate the results of the FEMA/SAC project. In addition, these provisions were modified to be consistent with the

ASCE 7 document, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2002). This allows the document to be incorporated by reference into upcoming editions of the IBC and NFPA 5000 building codes that will use ASCE 7 as their basis for design loadings.

As with the previous supplements to the 1997 provisions, a number of specific changes were made to make these provisions as current as possible. Some of the changes include the following:

- A clarification to the glossary to verify that chord and collector/drag elements in floor diaphragms are considered to be part of the seismic force resisting system and therefore must meet these provisions.

- Additional requirements for the toughness of filler metals to be used in certain complete-joint-penetration (CJP) groove welds in intermediate and special moment frame systems. CJP welds between beam and column flanges, between beam webs and shear tabs to column flanges, and column splices are the welds that are required to meet these requirements. These additional requirements include two level toughness specifications. The first level is the 20 ft-lb at -20 ºF as determined by AWS classification methods. This is consistent with the specification for toughness of all welds in the seismic load resisting system. The second level is 40 ft-lb at 70 ºF, as specified in a new appendix (Appendix X) based on the recommendations in FEMA 350 and FEMA 353 (FEMA, 2000a and 2000d). To ensure acceptable toughness for a range of applications, this new appendix requires testing in accordance with AWS A5 procedures with a range of heat inputs, preheat temperatures and interpass temperatures. With proper documentation and certification, the filler metal manufacturers can avoid lot testing. In addition, the appendix allows the fabricator/erector to qualify the weld metal for a wider or narrower range of heat inputs and interpass temperatures. In all cases, the Weld Procedure Specification for the various welds must be within the ranges tested. The appendix specifies the requirements for this testing and the acceptance procedures.

- A revision to clarify member slenderness ratio requirements and to better coordinate with the AISC LRFD provisions. A new term has been added to establish when slenderness ratios that are more restrictive than the requirements of Section B5 of the AISC LRFD Specification are required for critical members of the lateral force resisting system. In addition, a new entry has been added for the use of H-pile shapes in foundation elements.

- Increase the moment frame column splice requirements to reflect the FEMA/SAC recommendations. Specifically, the shear force on the column splices needs to develop plastic hinges at the top and bottom of each story. An exception is provided to reduce this requirement if special analyses are performed to demonstrate a lower demand.

- Add splice requirements for columns that are not part of the moment frames to develop a minimum shear force. This requirement was also generated from the FEMA/SAC recommendations that demonstrated the importance of continuity of these elements to the performance of moment frame systems. The shear force demand is required to be half of that for moment frame columns.

- Clarify column base design demands for various systems.

- Add a section on the use of H-pile members. Slenderness ratios for these elements have been assigned to be consistent with successful test results. All gravity loads are to be resisted by vertical piles, without the assistance of batter (sloped) piles. Mechanical methods must be used to transfer all loads between steel piles and the concrete pile cap (friction is not allowed). This section also limits the placement of any attachments to the piles in the expected area of plastic hinging just below the bottom of the pile cap.

- Clarify lateral bracing requirements of moment frame beams, including the provision of a required stiffness to be consistent with Section C3 of LRFD.

- Increase SMF web connection design requirements to be consistent with FEMA 350. This requires that the shear connection be able to develop plastic hinges due to seismic demand at each of the beams.

- A new appendix (Appendix P) that defines procedures to be used in the pre-qualification of moment connections. These recommendations are based on the FEMA/SAC program. The reason for including such an appendix is to provide designers with a mechanism to incorporate moment connections that have been extensively tested and analyzed on projects without the need to present connection test results. It is hoped that a national connection prequalification review panel (to be administered by an AISC committee established specifically for this purpose as discussed below) will be recognized by model building code entities and jurisdictional authorities to prequalify such connections. This appendix specifies an extensive series of variables that need to be considered in the prequalification process to ensure that the performance of the connection is well understood. Extensive complementary analyses and a design procedure must also be included as part of the prequalification. A standard set of information is to be provided to document the connection prequalification.

- Incorporate FEMA 350 recommendations for weld access holes in OMF systems. Access holes have been demonstrated to be a stress riser that can cause premature fracture. This access hole specification is the result of extensive testing and analysis work performed at Lehigh University. This specific access hole is specified for OMF systems because such systems can be designed without qualifying tests. For SMF and IMF systems, the access holes are to be consistent with the successful tests.

- Incorporate FEMA 350 recommendations for the removal of weld backing and run-off tabs in OMF systems, including grinding surfaces to adequate smoothness. The reason for including these requirements specifically for OMF systems is the same as that noted above for weld access holes.

- Provide new commentary to alert designers about potential net section weakness for HSS braces connected through a single gusset plate in concentrically braced steel frames.

- Update Parts II and III to be consistent with Part I.

- A major expansion to the Commentary to provide explanation to the changes that have occurred since the 1997 Seismic Provisions were developed, and to provide additional guidance that will help engineers in interpreting the provisions.

ANTICIPATED FUTURE DESIGN PROVISIONS FOR STEEL STRUCTURES

The experiences of the past decade have demonstrated that continuous attention should be paid to ensure the seismic design provisions for steel building structures remain as current as possible. A systematic process has been established to efficiently accomplish this goal. This process will rely on the AISC TC 9 subcommittee to develop specific code provisions for the various structural steel systems that will then be balloted through the main AISC Committee on Specifications. As an American National Standards Institute (ANSI) accredited consensus activity, this balloting and the subsequent document that will result will be a standards document that can be adopted by national building codes by reference. The BSSC TS6 subcommittee will focus primarily on the proper and consistent application of the design coefficients such as R, C_d, and Ω. This subcommittee will also likely introduce any new structural systems into the NEHRP documents. This will allow such new systems to be used on a provisional basis, so that actual building applications can be used to test the efficacy of the provisions. As experience is gained with these new systems, it is expected that they would then be able to be incorporated into the AISC Seismic Provisions and therefore, future editions of the building code.

Two such systems that are presently being developed and will likely be incorporated into the 2003 NEHRP Provisions are the Buckling-Restrained Braced Frame (BRBF) and the Steel Plate Shear Wall (SPSW). The BRBF system was originally developed in Japan, and has recently been used on a number of projects on the West Coast. This system relies on a brace element that is restrained from overall member buckling, thereby significantly increasing the energy dissipation of the system over that of a traditional CBF system. The provisions for the BRBF system were developed by a task force of the SEAOC Seismology Committee and AISC TC9. The SPSW system has been used on a number of buildings in high seismic regions dating back to the early 1970s. Renewed interest in this system developed in the 1990s in Canada as the result of a series of research projects at the University of British Columbia and the University of Alberta. The National Building Code of Canada has design provisions for this system based on the results of this research. Additional research on this system is presently being conducted at the University of California at Berkeley. The design provisions to be developed will be based on both of these research efforts.

Late in 2002, AISC also initiated a separate activity to develop a standard for the pre-qualification of seismic moment connections in accordance with Appendix P of the 2002 AISC Seismic Provisions. This committee will develop an ANSI approved standard (or group of standards) that will be for the application of specific moment connections in seismic design. Once this standard(s) is developed, it is expected that the national building codes will also adopt this standard by reference. As a standing review panel, the AISC Connection Prequalification Review Panel (CPRP) will continuously evaluate and update the connection prequalifications so that the standard is as current as possible.

As noted above, the primary responsibility for the development of the specific seismic design provisions for steel buildings will rest with AISC, and the prescription of design coefficients and development of new systems will be led by BSSC/NEHRP. These organizations will help to provide oversight and guidance to each other during this process. The American Welding Society also has a seismic subcommittee that is developing a document to specifically address welding related issues that relate specifically to seismic applications. This document will be an important link to the AISC Seismic Provisions, helping to ensure that the design intent is accomplished on the constructed projects.

CONCLUSIONS

Over the last ten years, a rational, systematic and efficient process has been instituted to incorporate the latest developments in seismic design of steel structures into building code provisions. This system relies on the coordinated efforts of AISC, BSSC, SEAOC and AWS committees. The process provides a single point of responsibility for the development of these provisions, thus eliminating duplicative effort, and more importantly, the development of competing documents that would result in minor differences that would undoubtedly result in major confusion in application by practicing engineers. The recent publication of the AISC 2002 Seismic Provisions will allow for this edition to be incorporated into the 2002 NFPA 5000 document and the 2003 IBC. As a result, the seismic design of all steel buildings in the United States will be governed by this document, allowing for engineers to easily develop their designs in a consistent fashion, no matter what the jurisdiction. This will lead to better designs, and better performance by steel buildings in future earthquakes.

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