SAC Steel Project

Update

funded by the Federal Emergency Management Agency

the FEMA Program to Reduce Earthquake Hazards in Steel Moment Frame Structures

No. 3

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New Seismic Design Criteria For Steel Frames in Development

More than forty major technical investigations are now underway across the United States as part of the Phase 2 FEMA-funded SAC Steel Project. During the coming months at least a dozen more investigations will be added. Results of these and other efforts will be synthesized and evaluated to produce Seismic Design Criteria for steel moment-resisting frames having welded, bolted and other types of connections. The Criteria will address issues related to:

- Design and construction of new steel moment frame structures;
- Inspection, evaluation, and retrofit of at-risk steel buildings prior to an earthquake; and
- Inspection, evaluation, repair, and modification following a damaging earthquake.

FEMA plans to publish these Criteria in the fourth quarter of 1999, along with six State-of-the-Art Reports, which summarize the technical basis of the new recommendations. The Seismic Design Criteria will replace the *Interim Guidelines: Evaluation, Repair, Modification and Design of Steel Moment Frames* (FEMA 267) developed during the first phase of the SAC Steel Project. In the meantime, the *Interim Guidelines* are being updated. The first *Supplement to the Interim Guidelines* (FEMA 267A) was published by FEMA in April 1997. Additional Supplements will be released throughout the project as warranted. In addition, a variety of Background Documents and Technical Reports are being released as investigations are completed. SAC Steel Project *Updates*, along with the SAC World Wide Web (WWW) site *{see below}*, provide information on the availability of these reports and other project information.

Development Schedule Set

The new Seismic Design Criteria will consist of five documents, each specifically organized to address concerns of a particular audience. The documents are:

1. Inspection Procedures
2. Quality Assurance and Control
3. Post-Earthquake Inspection, Evaluation, and Repair
4. Evaluation and Upgrading of Existing Buildings
5. Design of New Structures

These documents will contain detailed information related to:

- Post-Earthquake Inspection
- Post-Earthquake Evaluation
- Damage Repair
- Evaluation of Existing Bldgs.
- Struct. Performance Levels
- Base Metals and Fracture
- Loss Estimation
- New Building Design
- Structural Analysis
- Connection Qualification & Design
- Seismic Upgrading
- Quality Assurance & Control
- Welding
- Structural Specifications

A series of four drafts of the Seismic Design Criteria and supporting State-of-the-Art Reports is planned. Early drafts will focus on organization and format, while later ones will incorporate increasing amounts of technical detail. Final drafts will be the subject of trial applications and widespread public review. In order to integrate the results of the technical studies into the Seismic Design Criteria and to provide adequate opportunity for review and revision of the format and content, a staged schedule for the State-of-the-Art (SOA) Reports and the Seismic Design Criteria (SDC) has been defined as shown below.

			Schedule	
Draft	Focus	Review	SDC	SOA
25%	Table of Contents, Format, Issue Identification	Internal	1Q 1998	1Q 1998
50%	Format, First Technical Content	Internal & Workshop	1Q 1999	3Q 1998
75%	Expanded Technical Content	Workshop	2Q 1999	1Q 1999
100%	Final Edit	Broad External	4Q 1999	3Q 1999

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SAC is a joint venture of three non-profit organizations: The Structural Engineers Association of California, the Applied Technology Council, and California Universities for Research in Earthquake Engineering.

Highlights of Topical Investigations

Teams of investigators and technical specialists are studying the specific problems covered in the Seismic Design Criteria. Nationally representative Technical Advisory Panels have been convened to help identify the highest priority topics and interpret the results obtained. Preliminary results of some of these studies are presented here, and additional information can be found on the SAC WWW site.

Materials and Fracture - Two investigations are underway to better characterize the material properties of rolled steel sections typically used for moment frame construction. The first investigation, led by Karl Frank of the University of Texas at Austin, will statistically characterize properties (such as yield and ultimate tensile strengths and Charpy V-notch values) for a variety of section sizes and mills. The second study, being conducted at Lehigh University under the direction of Robert Dexter of the University of Minnesota, is experimentally and analytically evaluating the through-thickness properties of column flanges in the vicinity of a weld to a beam flange. A survey of through-thickness material properties has been prepared by Project Oversight Committee member John Barsom and Sjaan Korvink (*detailed article on page 7*). Other related tests will also be undertaken by the American Institute of Steel Construction. A workshop will be held later in the project to identify desired steel material properties.

Joining and Inspection - A series of six basic studies are now underway to understand the factors that contribute to weld behavior, and to predict performance of welded joints under different service conditions. Two of these studies, being conducted by the Battelle Institute in Ohio under the direction of Pingsha Dong, experimentally and analytically assess the effects of strength and toughness of the weld and base metal on performance at various loading rates. The sensitivity of observed behavior to variations in welding process, procedures and conditions are being studied in a related investigation at the Edison Welding Institute, under the direction of Matt Johnson. Based on the results of these and other studies, investigators in statistics, computer science, and metallurgy at the Colorado School of Mines under the direction of Manavandra Misra are developing semi-empirical methods for predicting the behavior of a particular weldment. The ability of current visual and ultrasonic inspection procedures to detect critical imperfections in weldments is being systematically evaluated for a series of typical joints encountered in moment frame construction by Glenn Light and others at the Southwest Research Institute. The results of these and other investigations are being evaluated by William Mohr of the Edison Welding Institute to develop performance-based criteria for weld acceptance.

Connection Performance - In addition to an extensive connection test program (see Connection Testing and Analysis below), several basic analytical investigations have been initiated to assess the factors that control the behavior of connections and to assess analytical methods for design and evaluation. Two studies involve detailed finite element analyses of a wide variety of welded connections. The first of these, by Greg Deierlein and Anthony Ingraffea of Cornell University, examines the ability of finite element models that simulate brittle fracture to predict observed behavior in a variety of previously tested connections, and to suggest design modifications that might improve behavior. A summary of this investigation is provided on *page 8*. A more extensive parametric study of unreinforced connections is underway assuming ductile behavior. A wide range of material properties, beam and column sizes, and connection geometries and details are being considered to better understand factors controlling plastic deformation demands and to identify conditions under which these connections might respond reliably. A SAC Background Report on this study has been authored by Sherif El-Tawil and Sashi Kunnath of the University of Central Florida. An additional finite-element-based study will be initiated soon to calibrate advanced analytical models using results from the Phase 2 materials, weldment, and connection tests, and to better understand the influence of construction sequence, residual stress, material properties, testing procedure, and connection configuration and detailing on performance of welded joints.

Tying all of these activities together is a project under the direction of Charles Roeder at the University of Washington to develop and evaluate straightforward design procedures for various moment frame connections employing welded, bolted and other joints.

System Performance - This group's studies are almost complete, and a number of reports summarizing their work are expected to be published in the first half of 1998. The investigators in this group are Paul Somerville (Woodward-Clyde Federal Services) - ground motions; Helmut Krawinkler (Stanford University) - benchmarking computer programs for nonlinear dynamic analysis of frames, and influence of proportioning, configuration and modeling on system performance; Farzad Naeim (John A. Martin and Associates) and Andrei Reinhorn (State University of New York at Buffalo) - influence of different types of hysteretic behavior; Gregory MacRae (University of Washington, Seattle) - influence of ground motion intensity and characteristics; Allin Cornell (Stanford University) - influence of fracturing connections on new and existing structures; and Kazuhiko Kasai (Lehigh University / Tokyo Institute of Technology) and Bruce Maison (consultant) - investigation of

Phase 2 Steel Program

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framing systems with bolted and partially restrained connections. Analyses were conducted based on a set of 18 model buildings located in different seismic zones around the U.S. *(for details see "Summary of Model Building Designs" on page 10)*. Results from the detailed nonlinear time history analyses undertaken by this group have been incorporated in an electronic database for use in the Performance Prediction and Evaluation studies described below.

Performance Prediction and Evaluation - The mission of this team is to develop quantitative procedures to assist in the development of performance-based guidelines for the design and evaluation of steel structures. Their first activity - specification of a reliability framework for the evaluation of predictive models considering uncertainty associated with ground motions, structural behavior, the type of analytical method used, and modeling assumptions - has been completed. It is available as a SAC Background Report, authored by Y.-K. Wen and Douglas Foutch of the University of Illinois at Urbana-Champaign. Linear and nonlinear analysis procedures are now being assessed and calibrated using new results as well as those provided by the System Performance team. These efforts are being led by James Anderson of the University of Southern California (linear methods) and Gary Hart of the University of California at Los Angeles (nonlinear methods). Team Leader Douglas Foutch is integrating these results on the basis of the reliability framework, and assessing special design and analysis needs for ordinary moment-resisting frames.

Connection Testing and Analysis

The first activity of the Connection Performance team was to outline a staged series of experimental investigations aimed at evaluating critical issues influencing the behavior of various types of steel beam-column connections. A detailed Test Protocol, including a revised loading history *(see page 9)*, was also established. In all of the tests, various phenomena (e.g., yielding, local buckling, fracture initiation) useful in establishing performance limit states will be carefully documented. The initial Test Plan outlined four large-scale connection test projects encompassing a total of 50 specimens. The following studies are now well underway:

- Experimental and Analytical Studies of Unreinforced (pre-Northridge) Connections - Principal Investigators: Subhash Goel and Bozidar Stojadinovic, University of Michigan; investigating the behavior of unreinforced connections and the influence of beam depth, relative beam, column and panel zone strengths, modified weld details and use of alternate consumables. *See photo below.*

Photo Credit: B. Stojadinovic

- Experimental and Analytical Studies of Bolted Connections - Principal Investigator: Roberto Leon, Georgia Tech University; investigating the behavior of bolted connections with particular emphasis on the mechanics and detailing of T-stub joints.
- Experimental and Analytical Studies of Simple Connections, Including Slab Effects - Principal Investigator: Abolhassan Astaneh, University of California at Berkeley; investigating the behavior of bolted non-moment-resisting shear connections with and without composite slabs to understand the contribution of these widely-used connections to the lateral resistance of steel frames. *See photo below.*

Photo Credit: A. Astaneh

- Experimental and Analytical Studies of Reduced Beam Section (RBS) Connections - Principal Investigators: Michael Engelhardt, University of Texas at Austin, and Gary Fry, Texas A&M University; investigating the applicability of RBS connections with particular emphasis on flange detailing, panel zone yielding, interior column vs. exterior column connections, and the influence of composite slabs on local and lateral torsional buckling.

Based on preliminary results from the topical investigations and discussions with design professionals, representatives from fabricators and technical experts, the Connection TAP has identified a second round of connection tests and analyses. Approximately 50 more specimens will be involved in this round of testing. These tests, to be initiated in March 1998, include investigations of:

- Retrofit of undamaged pre-Northridge-style connections.
- Modified, larger-sized, unreinforced connections including

integrated material and weldment tests.
- Welded flange plate connections, including cases with welded cover plates.
- Bolted flange plate connections, including cases permitting slippage due to friction.
- Bolted end plate connections.

In addition, a final series of confirmation tests is being planned in which other variables that may influence the behavior of beam-column connections will be studied (e.g., dynamic loading, loading history, column axial load and orientation, slab effects, variations in material properties, local details, member sizes, frame action, etc.), and limits of acceptable behavior will be determined for the connection types proposed in the Seismic Design Criteria. These confirmation tests will help substantiate the final recommendations for connection design and detailing.

Critical to understanding and interpreting the results of the experimental program is an integrated series of analytical studies. Each test project incorporates a parallel finite element analysis of the test specimens with the goal of calibrating analytical models to the observed behavior. As noted previously, another series of overarching nonlinear finite element studies is being conducted by the Connection Performance Team in which the influence of various general parameters (e.g. material properties, fracture behavior, residual stresses, connection geometry and details) are studied or in which results from several testing projects are compared. These analytical studies will be used in conjunction with the testing program and other information to define reliable limits on the applicability of particular connection details and analytical methods.

Past Performance of Steel Buildings Studied

To help understand the actual performance of steel buildings during earthquakes, a team has been established to gather and interpret additional information from the Los Angeles Area as well as from other earthquake sites around the world where steel buildings have been severely shaken. A wide variety of information on steel buildings damaged in Los Angeles is being systematically gathered and interpreted by Michael Durkin (consultant). Allan Porush, from Dames and Moore, Los Angeles and Peter Maranian of Brandow & Johnston Associates, Los Angeles, are extending the information gathered during Phase 1 on structural damage, and using this data to assess various evaluation procedures recommended in FEMA 267. Damage reports and on-site inspections of various buildings are being studied under the direction of Terrance Paret of Wiss, Janney, Elstner Associates, Emeryville, California, to assess the reliability of ultrasonic test procedures. Information on the demands imposed on the construction, financial, and insurance industries and on regulatory agencies by the damage to steel buildings in Los Angeles, is being gathered by James Goltz of Caltech (formerly of EQE, Irvine). Damage to steel frame buildings in other California earthquakes is being investigated by Maryann Phipps of Degenkolb Engineers, San Francisco. Cooperative arrangements have been made with the Architectural Institute of Japan to obtain detailed information on the performance of steel buildings in Kobe during the 1995 Hyogo-Ken Nanbu (Kobe) earthquake. Information gathered on the past performance of steel buildings will be synthesized, evaluated and reported under the direction of Charles Thiel (Telesis Engineers, Piedmont, California).

Team Studies Social, Economic, and Policy Implications

A panel of individuals with diverse backgrounds has been formed under the direction of L. Thomas Tobin (Tobin and Associates, Mill Valley, California) to assess the social, economic, and policy impacts of the design recommendations being developed in Phase 2. This group represents perspectives from the legal, insurance, and construction professions as well as from building owners, tenants, code officials, and policy makers. Their primary role is to help identify issues to be addressed by the guideline writers, including incentives toward and barriers against the adoption of improved design criteria. Early consideration of these social and economic influences will help ensure that any proposed recommendations will be more readily accepted.

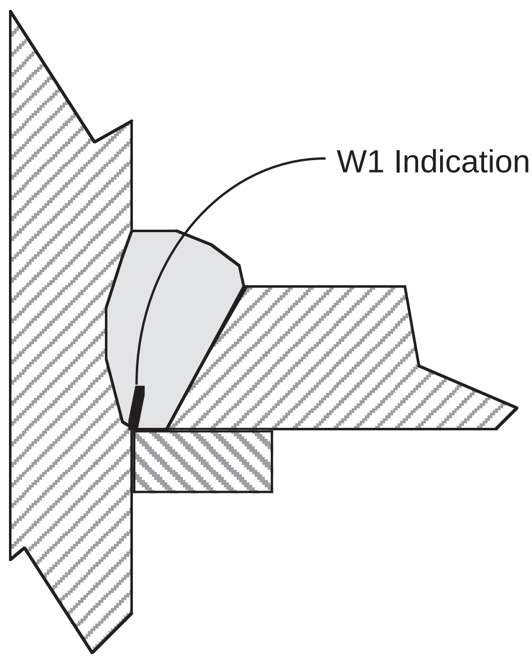
Two early meetings of the 10-person panel identified several key items. These were addressed at a Workshop on Social, Economic, and Policy Issues held in late October 1997. In attendance at the Workshop were the SAC guideline writers and topical team leaders (the two groups leading the guidelines development and research activities), members of the SAC Project Oversight Committee representing stake holders in professional practice, industry, government, and research; and the SAC project directors. Multi-disciplinary breakout groups were structured around three distinct categories of construction: new buildings, existing at-risk buildings, and buildings in a post-earthquake environment. This format allowed various socioeconomic perspectives (owners/lenders/insurers, building officials/construction/policy, and law/legislative) to be examined in turn and focused discussions on various design, upgrade, and evaluation/repair scenarios.

Proceedings from the Workshop, scheduled for publication in the second quarter of 1998, will provide direction for the guideline writers' ongoing efforts to draft design recommendations. Several action items related to implementation issues will also be identified in a separate document. This document will assist the process of nationwide education and building code development anticipated to be undertaken in the optional final year of the contract between FEMA and SAC. Further information on the activities of the Social, Economic, and Policy Panel will be provided in future *Updates*.

W1 Damage Conditions

Chapter 3 of FEMA-267, *Interim Guidelines: Evaluation, Repair, Modification and Design of Welded Steel Moment Frame Structures*, provides a system for categorizing and reporting damage of different types. In Chapter 4, these damage classifications form the basis for calculation of damage indices, which are used to determine post-earthquake repair and occupancy programs. By far the most common forms of damage reported in buildings affected by the Northridge Earthquake, termed W1, are rejectable conditions at the root of the full penetration welded joint of the beam bottom flange to the column flange. This weld root is typically obscured by the weld backing and, as a consequence, these indications can be detected only by means of ultrasonic examination, or visual inspection after removal of the backing.

During preparation of FEMA-267, there was considerable discussion as to whether these W1 indications were actually damage or rather previously undetected construction defects. The large number of W1 indications found in buildings following the Northridge Earthquake, the fact that these W1s were rejectable conditions under the AWS D1.1 code, and also that these buildings had all been subject to special inspection during construction supported the concept that W1s were caused, or at least made more severe, by the buildings' response to ground shaking. However, fracture mechanics analyses suggest that the inherent low toughness of the weld metal commonly present in existing buildings would result in a low probability of a fracture being arrested within the body of the weld, prior to extending either completely through the material, or into the tougher base metal.



Typical W1 Condition

Growing evidence now suggests more strongly that many W1s are not earthquake-caused damage. Terry Paret (Wiss, Janney, Elstner Associates, Emeryville, California) has presented evidence that supports the possibility that many rejectable flaws were overlooked during the construction inspection process. (see Paret, T.F., and Freeman, S.A. "Is Steel Frame Damage Being Diagnosed Properly?" Proc. of ASCE Structures Congress '97, April 14-16, 1997, Portland.) Paret suggests that ultrasonic testing (UT) of beam bottom flange welds during construction is commonly conducted from a "wild cat" position along the top surface of the flange. The geometry of the UT sensor and the welded joint itself prevents an accurate reading of weld root conditions for thick flanges. However, when inspections are performed following an earthquake, readings are typically taken along the bottom surface of the flange, where these geometric restrictions are not present, permitting the detection of indications not observable from the top flange scanning surface.

In response to this finding, SAC recently participated in investigation of a building in San Francisco that was undergoing voluntary seismic upgrade. Prior to removal of weld backing, UT sensing was performed from several faces of the joint, and then visual inspection was performed after removal of the backing. It was confirmed that UT scans performed from the top and bottom surfaces of the beam flange resulted in different findings. However, it was also determined that upon removal of weld backing, indications found by both approaches often were not present. This tends to suggest a general lack of reliability in the UT inspection technique as currently applied.

Several experimental investigations have addressed this dilemma. During NSF-sponsored tests by Robero Leon and Jerry Hajjar (University of Minnesota), sensitive acoustic equipment was installed on a beam bottom flange. Results obtained show the incremental growth of indications. More information can be found in "Seismic Response of Composite Moment-Resisting Connections," J.F. Hajjar, et al, submitted to *ASCE Journal of Structural Engineering.*

Several investigations of inspection methods are underway as part of the Phase 2 program. Preliminary UT and visual inspections of pre-Northridge connections being tested at the University of Michigan, Ann Arbor, indicate that indications grow during tests prior to total fracture. A series of mock-ups of various types of welded joints are being fabricated by the Southwest Research Institute in San Antonio, Texas. Electronic discharge machining and other methods are being used to insert known defects. Blind tests by a variety of laboratories and technicians, using several inspection procedures, will be used to help assess the reliability of UT inspection.

Despite the apparent difficulty of accurately detecting the presence of W1 conditions, recent analytical studies conducted by Dr. Greg Deierlein at Cornell University suggest that they are critically important to the behavior of pre-Northridge connections. (Deierlein, G.G. et. al. "Finite Element Fracture Mechanics Investigation of Welded Beam Column Connections", SAC/BD-97/05, December, 1997.). Deierlein concluded that large W1 conditions at the root of the bottom flange joint are more likely to lead to brittle fracture initiation than the notch effect created by the presence of the weld backing. Given the apparent unreliability of UT inspection, this confirms the importance of backing removal, both as a means of removing the notch effect and ensuring acceptable conditions at the weld root.

SAC is continuing to investigate the W1 phenomenon to determine conclusively whether these conditions are the result of earthquake response or construction deficiencies. In addition, SAC is working to identify more reliable means of conducting construction quality assurance inspections.

SAC Phase 2 Ground Motions

Paul Somerville and Nancy Smith

The implementation of performance-based design methods requires more detailed specification of input ground motions than in the case of conventional design procedures. In particular, many of the methods being used in the design and analysis of buildings for performance-based design, including those being used in the SAC Steel Project, require ground motion time history inputs.

Ground motion time histories and response spectra are being used in the SAC Phase 2 Project as part of the topical investigations, case studies, and trial applications. The time histories were developed by Dr. Paul Somerville in the Pasadena Office of Woodward-Clyde, assisted by Ms. Nancy Smith (Pasadena), Dr. Sujan Punyamurthula (Seattle), and Dr. Joseph Sun (Oakland). Time histories were developed for Boston, Seattle and Los Angeles, which represent a range of seismic hazard levels from UBC Zone 2 to Zone 4. For each location, two suites of ten time histories each were generated to represent ground motions having probabilities of exceedance of 10% in 50 years and 2% in 50 years. Each ground motion is represented by a scaled set of a vertical and two horizontal components. In addition, a suite of ten time histories was generated for Los Angeles to represent ground motions having probabilities of exceedance of 50% in 50 years. The time histories have magnitude-distance pairs that are compatible with deaggregation of the probabilistic seismic hazard for the site. In most cases recorded ground motions were modified, if needed, to build up the suites. Generally, not enough recorded time histories appropriate for the required magnitudes, distances and site conditions were available, so time histories generated by broadband strong motion simulation methods were used to supplement recorded time histories.

Individual time histories were scaled so that their response spectra are compatible with the spectral ordinates from the 1997 NEHRP probabilistic ground motion maps, adjusted for site conditions from soft rock to stiff soil (from S_B/S_C boundary to S_D), in the period range of 0.3 to 4 seconds. These adjusted target response spectra ordinates are shown below.

Maximum Considered ground motion maps have been developed by the Building Seismic Safety Council and the USGS. In Boston and Seattle, these ground motions are identical to those for 2% in 50 years, and in Los Angeles they are so close that the difference between them (less than 10%) is not significant. Accordingly, the time histories for 2% in 50 years can be used to represent the Maximum Considered ground motions for all three locations.

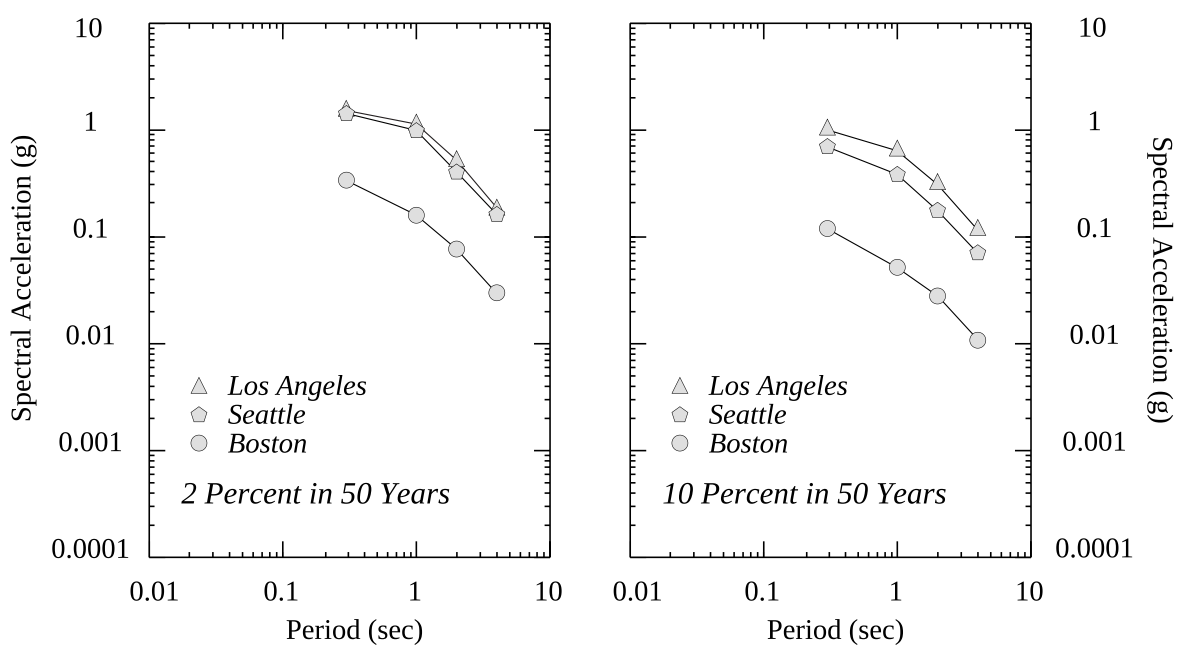
In addition to the 10 time histories for stiff soil conditions for 10% in 50 years for each location, a suite of 60 time histories was generated for each location using the 10 stiff soil time histories as inputs into six different soft soil profiles that were the same for each location. In addition, a suite of 20 other time histories was provided to represent near-fault ground motions from large earthquakes in Zone 4.

To access portions of the report describing the ground motion time histories developed for the SAC Phase 2 project (SAC/BD-97/04), or to download ground motion time histories, go to the web page:

http://quiver.eerc.berkeley.edu:8080/studies/system/ground_motions.html.

The horizontal component time histories of the 10 percent in 50 years, 2 percent in 50 years, and soft-soil records in this directory are rotated 45 degrees from the fault strike direction. The near-fault time histories are rotated into strike-normal and strike-parallel components, which maximize near-fault rupture directivity effects. Inquiries about the time histories can be addressed to Dr. Paul Somerville at pgsomer0@wcc.com or Ms. Nancy Smith at nfsmith0@wcc.com.

Target Spectral Ordinates for Scaling Phase 2 Time Histories



Through-Thickness Properties of Structural Steels

John M. Barsom & Sjaan A. Korvink

Typical beam-column moment connections must transfer beam flange tensile forces to the column panel zone by pulling the column flange in the through-thickness direction. In the past, there had been a history of lamellar tearing failures of thick column flanges under the influence of fabrication-induced shrinkage stress. Improved detailing and inspection practice has greatly reduced the severity of this problem in recent years. However, the discovery of column flange "divot" failures (Fig. 1) in buildings damaged by the Northridge Earthquake, has again brought into question the ability of heavy rolled steel shape to resist large through-thickness (TT) tensile demands. The through-thickness properties of structural steel are not routinely tested and consequently, when FEMA 267 was first published, no firm recommendations could be included with regard to appropriate limiting TT stresses.

Figure 1
Divot Failure in Column Flange

In addition to iron and carbon, steel includes a number of other elements including manganese, phosphorous, sulfur, and silicon. As cast steel cools, manganese sulfides form as independent inclusions within the surrounding metallic matrix. The rolling process used to produce structural shapes tends to flatten these inclusions and align them along the direction of rolling, and anisotropic mechanical properties can result. The degree of this anisotropic behavior is related to the amount of sulfur present in the steel as well as the extent the material is worked during the rolling process. Steels with superior TT properties can be obtained by controlling these parameters, and steel with excellent TT properties is commercially available in plate.

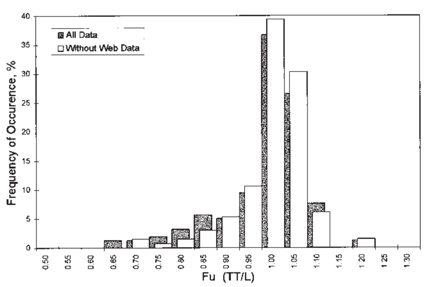


Figure 3
Distribution of TT/Longitudinal Fu

Although research into the TT properties of contemporary steels is limited, a significant body of research is available from the 1970s for plate produced by the basic oxygen and electric furnace processes and cast in continuous slabs and ingots, and for heavy shapes produced by the basic oxygen process and cast in ingots. Fig. 2, 3 and 4 respectively show histograms of the ratio of TT yield strength, ultimate tensile strength, and reduction of area (R.A.) properties to the comparable longitudinal properties for the same material obtained from selected historic data. As can be seen from the histograms, 80% of the specimens exhibited TT yield strengths within 10% of the longitudinal value and less than 5% of the specimens exhibited strengths lower than 90% of the longitudinal value. The scatter for ultimate tensile strength is somewhat larger, but less than 5% of the specimens exhibited strengths lower than 80% of the longitudinal values. The histogram for reduction of area indicates very large scatter with the expected values for the TT property significantly below those in the longitudinal direction.

The triaxial state of stress at a beam-column moment connection inhibits plastic deformation in the TT direction. Consequently, the TT yield strength of the steel in an actual connection is significantly higher than the values obtained by testing the conventional axisymmetric uniaxial specimen.

The results contained in this data base were generally obtained by testing small diameter coupons. Such tests tend to exaggerate the effects of local inclusions and discontinuities relative to the behavior of larger specimens, and thus probably over-estimate the anisotropic properties relative to the behavior of column flanges in moment resisting connections. It is also worth noting that in this database of test results, modern material taken from heavy rolled shape produced by the continuous casting process is not represented. It is anticipated that the TT properties of contemporary column shape would exceed, or at least not be worse than, those indicated in this sample. Through-thickness testing of contemporary steel material that will be used to supplement this data base is currently being conducted for the SAC Joint Venture at Lehigh University by Robert Dexter.

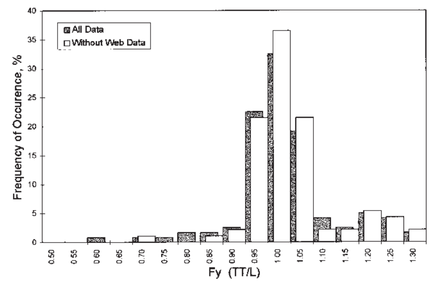


Figure 2
Distribution of TT/Longitudinal Fy

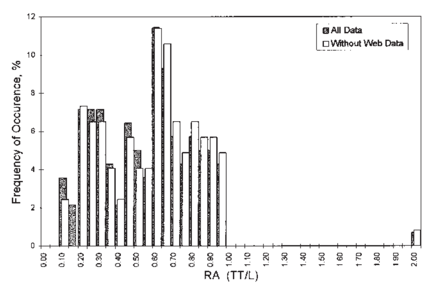


Figure 4
Distribution of TT/Longitudinal R.A.

Based on the data presented here, it is possible to draw preliminary conclusions with regard to design for TT behavior in moment-resisting connections. The wide scatter and reduced values for the reduction of area property confirm that TT yielding of column flange material should be avoided. It appears that TT yield and tensile strengths can be assumed with reasonable certainty to be in excess of 90% and 80%, respectively, of the corresponding longitudinal values.

This article is a summary of a Background Document (SAC/BD-97/01) prepared for the SAC Joint Venture by John M. Barsom and Sjaan A. Korvink. SAC wishes to acknowledge this voluntary contribution and thank the researchers for their assistance.

Quantifying Welded Moment Connection Fracture Toughness Demands

Gregory Deierlein, Anthony Ingraffea, and Wei-Ming Chi

One of the key issues in developing, ductile fracture-resistant connections is determining the toughness demand on the weld and base metal. Proposed modifications to welded connections such as the use of cover plates or reduced beam sections are intended to reduce the toughness demands, but their effectiveness has yet to be fully established. As part of Phase 2 of the SAC Steel Project, the authors have conducted a series of detailed finite element fracture analyses with the following objectives:

1. Demonstrate the accuracy of finite element fracture analyses to predict observed behavior,
2. Identify and improve understanding of parameters that influence toughness demand, and
3. Provide the groundwork for developing a methodology based on fracture mechanics to design fracture-resistant connections.

Studies for the SAC Steel Project conducted at Cornell University include analyses of connection subassemblies consisting of W14 x 257 columns and W36 x 150 beams that were previously tested at the University of Texas at Austin and the University of California at Berkeley (Report No. SAC 96-01, “Experimental Investigations of Beam- Column Subassemblages”). Connection types included both the standard pre-Northridge welded flange-bolted web detail and a post-Northridge cover-plate detail designed according to the SAC Interim Guidelines (FEMA 267). The study includes two- and three-dimensional elastic and inelastic analyses that evaluate crack initiation and propagation.

As shown in Figure 1, the analyses involved very refined meshing to investigate fracture in the lower beam flange weld. The magnified view of the beam flange weld in Figure 2 shows an example from an analysis with an initial edge crack (flaw) located in the weld metal near the column face. The shaded regions of the mesh correspond to portions of the material that yielded under the applied loading. Note the yielded region around the crack tip that has a shape characteristic of plane strain fracture conditions. Fracture toughness demands at crack tips are calculated through two fracture toughness indices. One is the stress intensity factor K_I - a measure of toughness demand based on elastic fracture mechanics, and the second is the Crack Tip Opening Displacement, CTOD - a measure of incipient tearing where there is significant plastification around the crack tip. The calculated K_I and CTOD indices are comparable to critical values determined from fracture toughness data for the weld and base metals.

In addition to confirming that toughness demands in the pre-Northridge details greatly exceed the toughness provided by the E70T-4 welds commonly used in these connections, these analyses have identified a number of parameters whose influence on fracture resistance warrant further consideration. For example, the ratio of the weld metal to beam flange yield strength appears to have a significant effect on weld toughness demands, suggesting that it may be appropriate to investigate the use of overmatching rather than matching electrodes. On the other hand, comparisons between the unreinforced and cover-plate connections indicate that the cover-plates may not be as effective in reducing toughness demands as may be desired. The analyses have also identified the effect of certain parameters such as column axial loads on crack trajectories. Further observations and details from the analyses are available in SAC Background Document SAC/BD-97/05, “Finite Element Fracture Mechanics Investigation of Welded Beam-Column Conections.”

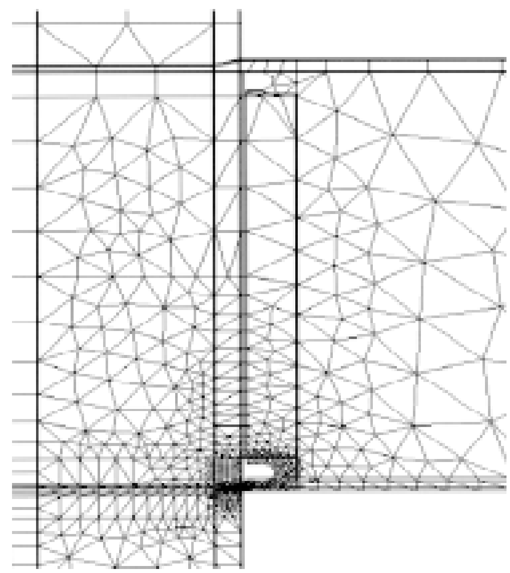


Figure 1
Finite Element Mesh

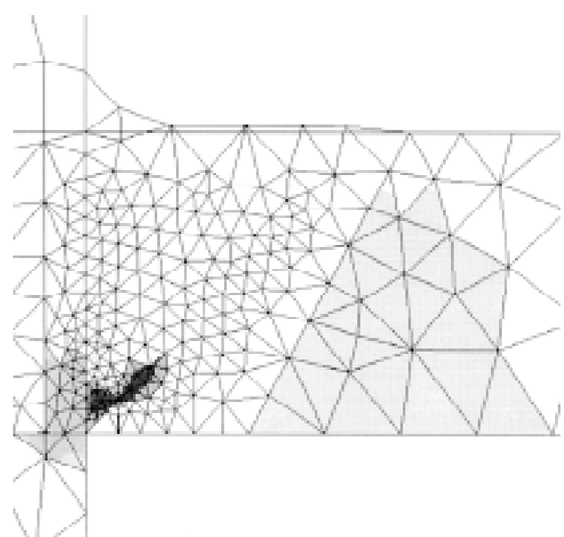


Figure 2
Plastified Regions in Vicinity of Weld Flaw

Test Protocol Document Available

In support of the large-scale beam-column connection tests now underway in the SAC Phase 2 Project, a document has been published specifying detailed procedures for fabricating, instrumenting, and testing specimens, and for reporting data. Background Document SAC/BD-97/02, “Protocol for Fabrication, Inspection, Testing, and Documentation of Beam-Column Connection Tests and Other Experimental Specimens,” consists of an introductory section and several appendices which address the following aspects of a connection test program.

Weld Procedure Specifications (WPS’s) - Guideline WPS’s have been developed appropriate to a number of joint configurations. These are used by the individual investigators to develop detailed WPS’s for their particular specimens.

Guidelines for Weld Quality and Inspection, and Bolting - General issues related to quality assurance for welded joints are covered, with emphasis on providing thorough documentation of the fabrication and inspection process. Bolted joints in beam-column connection subassemblages are required to conform to a separate set of specifications.

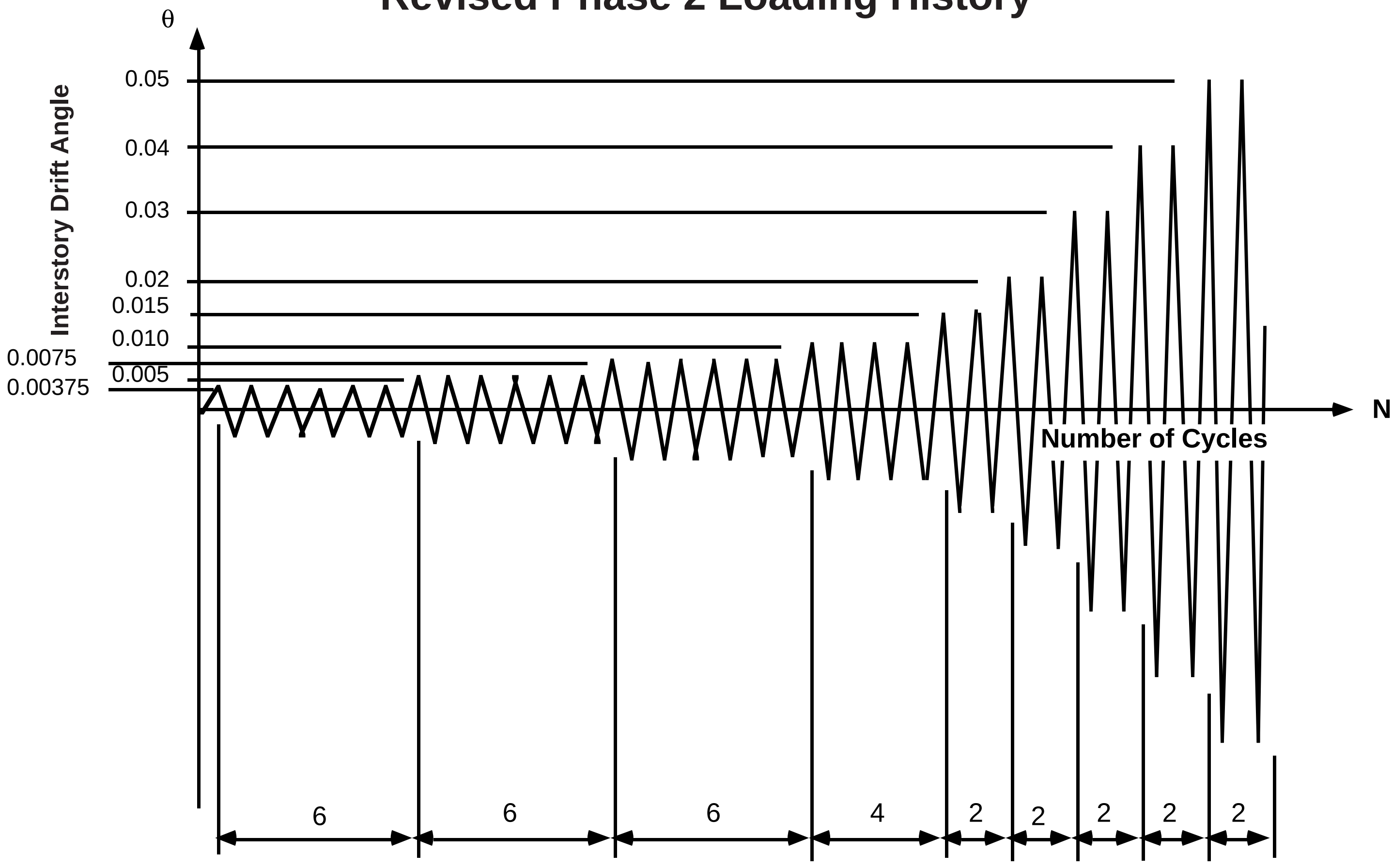
Guidelines for Tension Testing of Rolled Shapes - All steel materials used in the connection testing program are required to be tested according to these ASTM compatible procedures to ensure that the reported material properties are consistent with those obtained in the Materials and Fracture investigations.

Loading Protocol for Stepwise Increasing Cyclic Tests - Derived from a series of nonlinear time history analyses of the 3-story Los Angeles model building, a revised loading history (*below*) is being used in the Phase 2 Steel Project. Total rotation (θ), representing interstory drift, is the selected control parameter. Connection demands resulting from the application of this loading history vary slightly from those obtained in tests using the ATC-24 protocol.

Instrumentation/Data Acquisition and Reporting Requirements - General recommendations to provide consistent and reliable data and derived response quantities from connection tests are included to ensure that reported results from various specimens, investigators, and test laboratories are comparable and of appropriate accuracy for the development of design criteria.

Although this document has been developed specifically for use by investigators in the SAC program, it may be of interest to other organizations conducting large-scale beam column tests. However, it is not intended for use on specific building projects.

Revised Phase 2 Loading History



Summary of Model Building Designs

A series of model buildings have been designed to form a basis for analytical and cost impact investigations as part of the SAC Phase 2 Project. These buildings, which are assumed to be located on firm soil sites, consist of simple framing configurations with commonly-used bay spacings, and heights of three, nine and twenty stories. Three buildings have been designed in each of three typical cities intended to represent areas of high, moderate and low seismicity (Los Angeles, Seattle and Boston). Practicing structural engineering consultants with significant experience in this form of construction in each city participated in this activity, including Brandow & Johnston Associates (Los Angeles), KPFF Consulting Engineers (Seattle), and Lemessurier Consultants (Boston). Stanley Lindsey and Associates (Atlanta) has also performed trial designs of these buildings using partially-restrained connections. The buildings were first designed to meet the code requirements and standards of practice that existed prior to the 1994 Northridge Earthquake. Subsequently, all of the buildings were re-designed to meet the recommendations presented in FEMA 267. Finally, several different parameters (e.g., moment connection details, material strength, designs as close to the maximum allowed interstory drift) were varied, and individual "post-Northridge" buildings were re-designed.

These model designs serve as a basis for a number of studies in the SAC Steel Project, by providing the following:

1. A means of cost comparison between pre-Northridge and post-Northridge designs and a means of cost comparison between various post- Northridge alternatives.
2. A means of understanding the various design and construction implications of incorporating the FEMA 267 Interim Guidelines.
3. Information on areas of the Interim Guidelines that may require clarification or further information.
4. A basis for conducting detailed system performance investigations and performance prediction studies.
5. A basis for future trial applications of the draft Seismic Design Criteria document.

Some of the general initial conclusions resulting from these designs include the following.

- The moment frame member sizes did not change significantly between the pre-Northridge and FEMA 267 designs, although column sizes tend to increase slightly in order to maintain the same ratio of beam-to-column strength.
- The use of continuity plates and the size of web doubler plates increased.
- Moment connection welding procedures became significantly more expensive in terms of materials, labor and inspection.
- Wind-induced drift limits control the design of the nine story building in Boston and the twenty-story buildings.
- Seismic drift limits typically controlled the frame member designs for the other buildings, although the strength design requirements controlled the design of some members in the FEMA 267 designs in buildings in regions of high seismicity.

To assess the economic impact of various design approaches, Adamson Associates of San Francisco has been working closely with fabricators to develop cost estimates for the model building designs.

Significantly, the cost implications of incorporating the FEMA 267 guidelines are relatively small (on the order of few per cent) in relation to the total building cost. It is expected that reductions in the additional costs will occur as more definitive guidance is provided, causing more consistent construction requirements on different projects.

Links Around the World

To review information from around the United States and the world for possible incorporation in the new Seismic Design Criteria, the SAC project is maintaining liaison with a number of organizations and research entities. In the United States, SAC participants are involved in committees related to the seismic design of steel buildings for the American Institute of Steel Construction, the American Welding Society, and the American Society of Civil Engineers. There is also extensive sharing of information with federal research sponsors including the National Science Foundation and the National Institute of Standards and Technology. Both of these organizations have been supporting investigations which are directly applicable to the SAC guidelines development effort. NSF has recently announced a new research program in support of advanced steel structures as part of its U.S.-Japan Cooperative Research Program to Mitigate Urban Earthquake Disasters. Support from industry is being provided in the form of donations of material, fabrication, and inspection services and participation in various advisory committees. In particular, the Structural Shape Producers Council is contributing steel materials for the materials and large-scale beam-column connection testing programs, the American Iron and Steel Institute is providing plate material for the joint tests, and Lincoln Electric Company is

Information Requested on Inspection Technologies

The Steel Project is soliciting information on innovative technologies capable of providing practical and cost effective identification of fractures in welded framing connections. Current technology requires removal of finishes and fireproofing, and a combination of visual and ultrasonic inspection techniques. This approach is costly and disrupts building occupants. Technologies and applications that can provide reliable identification and quantification of damage at reduced cost and disruption are sought. New technologies for use during construction are also sought. Limited funding for demonstration of promising technologies may be made available.

Information should be sent to the attention of Peter Clark at the SAC Technical Office. Any information submitted should be considered non-proprietary and may be subsequently released to the public.

donating weld-wire for these activities. Other organizations or individuals that are interested in establishing liaison with the Phase 2 effort are asked to contact SAC directly.

In the wake of the 1995 Hyogo-Ken Nanbu (Kobe) earthquake, a great deal of research and development activity related to steel frame construction has been initiated in Japan. SAC investigators and project directors are staying abreast of progress in several Japanese programs, including those sponsored by the Building Research Institute and Kozai Club; the Architectural Institute of Japan; and the Japan Science and Technology Agency. A number of U.S. researchers and practitioners will meet with their Japanese counterparts at a U.S.-Japan Workshop on Steel Fracture Issues and Advanced Design Concepts to be held in Japan in April of 1998 with funding provided by the National Science Foundation. Participants in the Workshop will identify areas of common interest to the United States and Japanese construction communities and will continue to expand upon the collaborative efforts initiated at two previous meetings held in the U.S. in June, 1996, and February, 1997.

New SAC Publications To Be Released

In the coming months, several publications are being issued by FEMA and the SAC Joint Venture to provide additional guidance for the design of steel moment resisting frames. The SAC web site can be consulted to find the latest information.

Scheduled to be published in the first quarter of 1998 is a comprehensive database of publicly available connection tests performed in the U.S. and Canada since the 1994 Northridge Earthquake. This document has been assembled by David Bonowitz (consultant) under SAC funding and categorizes test results through a wide range of variables such as material characteristics, beam and column size, connection type, and ultimate rotation capacity. This information will be published in concise form as a FEMA report and will also be available as a database on the SAC WWW site.

A complete update of the *Interim Guidelines* (FEMA 267), originally published in Phase 1 of the FEMA-funded SAC effort, is scheduled to be prepared in the second half of 1998. After *Supplement No. 1 to the Interim Guidelines* (FEMA 267A) was published in April 1997, ongoing technical investigations both within and outside the SAC project are providing additional understanding and clarification of a number of issues of importance to the design and construction community. Publication later in 1998 or early 1999 of an up-to-date revision of the *Interim Guidelines* will ensure that such information is disseminated in a timely manner. It is likely that this revision will represent the last major change in the existing recommendations until the final Seismic Design Criteria are published in the fourth quarter of 1999. Brief Design Advisories will be issued as warranted. Individuals or organizations that would like to suggest non-proprietary technical issues to be considered in the upcoming revision or Advisories are encouraged to contact the SAC Technical Office and to provide any supporting documentation for consideration by the guidelines development team.

A separate series of publications is being prepared to disseminate results from technical investigations and other activities in the SAC project. Known as Background Documents, these reports generally reflect interim findings of narrowly-focused activities, do not provide general design guidance, and are not subjected to review prior to release. As such, these documents are appropriately accompanied by a strong disclaimer. Workshop proceedings, non-published research materials from outside of the SAC project, and the final reports from the topical investigations and testing programs are examples of the documents included in this series. These are distributed upon request (see attached order form) at a cost set to cover printing and shipping.

Metropolitan Areas Where SAC Investigations Are Underway or Complete

Legend

- ● Consultants/advisors (total is approximately 170).
- ○ Testing, analysis or other investigations (total is approximately 75).
- ◉ Both consultants/advisors and testing, analysis or other investigations.

New Patents on Steel Connections Announced

The U.S. Patent Office has announced several new patents related to steel connections. Patent names and numbers are presented below as a public service:

5,595,040 (Chen)	Beam to Column Connection.
5,600,017 (Houghton)	Steel Moment Resisting Frame/Beam to Column Connections
5,628,156 (Tarics)	Moment Resisting Frame having cruciform columns and beam connections, and method for use therewith.
5,680,738 (Allen)	Steel Frame Stress Reduction Connection

More information on these and other patents related to steel construction can be obtained from the U.S. Patent and Trademark Office at their web site [http://www.uspto.gov] Copies of the patents may be obtained by calling the patent office at: 1-800-786-9199.

Mailing List

If you would like to be added to the SAC Steel Project mailing list to receive future *Updates* and notification of other reports as they become available, please mail or fax us the form below. (**You are already on the list if this *Update* was mailed to you.** If there is an error in your mailing label, please correct it below.)

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fax: ________________________________

e-mail: ________________________________

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