1. Introduction and Overview

This document has been developed to ensure that beam-column connection tests and other experimental activities undertaken in the Phase 2 Steel Project provide results which are consistent and comparable among all investigators and are of maximum utility in the development of new *Seismic Design Criteria* for steel moment frame structures. The methodologies presented here have evolved from experience in the Phase 1 test program as well as numerous other experimental programs not related to SAC. This document is intended for use by investigators in the Phase 2 Steel Project and presents only test procedures and methods. It does not address issues of acceptance of test results or suitability of details utilized for a particular application.

The scope of the document covers controls on steel materials and materials testing requirements, detailed fabrication and inspection provisions for both welded and bolted joints, considerations for test set-up and instrumentation of large-scale steel beam-column connection specimens, applied displacement loading histories consistent with anticipated seismic demands on connections, and data reduction and reporting protocols. Many of these provisions are included in Appendices A through F. Checklists for simplified fabrication and test reporting are provided in Appendix G. Submittal requirements are noted throughout the document, typically at the end of each section and at the each appendix.

Guide Weld Procedure Specifications (WPS's) are provided in Appendix A. Ranges are given for various process parameters, and it is expected that individual investigators, in conjunction with their fabricators, identify and report specific values of these parameters appropriate for particular welded joints.

The fabrication and inspection requirements given in Appendices B through C are typically beyond what would be prescribed in current code provisions and are therefore not appropriate for use in actual shop or field applications. However, numerous references are made to published codes and standards (from organizations such as ASTM, AWS, AISC, RCSC), and this document is meant to be used in conjunction with these other sources.

The materials testing requirements (Appendix D) and loading protocol (Appendix E) have been developed specifically for the SAC project to be consistent with ongoing studies in other topical areas. It is important that these be followed closely to ensure comparable data is obtained throughout the project.

The proposed instrumentation requirements (Appendix F) are intended to provide a minimum set of consistent recordings, though they will likely be augmented by individual investigators. Approval is required for an investigator to eliminate channels from the basic set. A complete instrumentation plan must be submitted prior to commencing each series of tests.

2. General Requirements

<u>Definition of a "Specimen"</u>

For the purposes of this document, a "specimen" is defined as a connection assemblage of a single configuration subjected to a consecutive series of loading histories. The specimen may not be altered (other than as a result of the applied loading) in any way over the course of testing; otherwise it should be considered as a separate specimen. This does not include changes to instrumentation (for instance the addition or removal of a channel in the middle of a test), but includes physical modifications, for example repairing or altering of cracks or other fractures, adding stiffening or reinforcing elements to unstable portions of the specimen, changing the test set-up, etc.

Traceability

One of the primary goals of this document is to provide traceability of the construction of the specimen and the generated experimental data, enabling this data to be evaluated by other investigators, enhancing its usefulness in future analytical studies, and ensuring its validity for the development of new design approaches and connection details. Considerations for the instrumentation and data acquisition include identification and calibration of all instruments, documenting all installation details, definitions of positive directions of instrumentation, and discussion of any data processing procedures (smoothing, averaging, filtering, etc.), and data storage and archiving plans.

There should also be traceability of the specimen, including maintenance of records from the entire materials procurement, fabrication, and inspection process. Detailed notes should also be kept during testing. Any deviations from specified procedures should be noted, and all records should be kept by the investigators for a minimum of three years after the completion of the test program.

Exceptions / Changes to Test Protocol During Testing

The specific loading protocol to be followed for all beam-column connnection tests is provided in Appendix E. Prior to testing, potential failure mechanisms — such as premature weld fracture, excessive specimen twisting, damage to shear connections or slabs, failure of one beam in a two-sided test set-up, etc. — should be identified, and consideration given to alternate courses of action to be taken should these failures develop, including stopping a test or changing the loading history. In the majority of these cases, the original loading should be followed until the resistance of the specimen deteriorates below 40% of the observed peak load. Still, it is likely that unexpected or unpredictable behavior will be observed, and the investigator is expected to act in the best interests of the investigation in determining whether to deviate from the specified protocol in a given case. If substantial alterations to the specimen itself are recommended prior to resuming testing, notification to SAC is warranted if time is available.

3. Pre-Test Activities

Design Drawings

Detailed engineering drawings of the test set-up and specimen details should be provided to SAC prior to fabrication of the test apparatus and the individual specimens. These should be in sufficient detail such that they can be used for construction of additional, identical specimens at a later date.

Materials Procurement, Fabrication, and Inspection

Controls shall be put in place by the investigator and the fabricator such that all steel materials delivered to the fabricator will be identified and set aside for use in the SAC testing program. Substitution of alternate materials is not allowed. A meeting shall be arranged between the investigator and the fabricator prior to initiating fabrication to discuss appropriate controls and procedures for meeting the specified WPS's, inspection, and bolting provisions presented in this document.

The WPS's provided in Appendix A shall be used as a baseline for developing specific WPS's for particular joint details. These specific WPS's shall be developed by the fabricator and investigator and submitted for review. Where ranges are given in the baseline WPS's, an attempt should be made to implement values near the middle of each range as appropriate for the actual plate thicknesses and other conditions present in the connection in order to achieve a heat input at the target level. Differences between root pass parameters and subsequent passes shall be documented. Additional details on development and implementation of WPS's are provided in Appendix B. In all cases, the parameters used at the time the specimen is fabricated must be documented. Examples of items which must be documented include preheat and interpass temperature, amperage, voltage, travel speed, electrical stickout, layer thickness and layer width, etc. A comprehensive fabrication checklist is provided in Appendix G.

All fabrication should be consistent with the restrictions imposed on actual construction. Both shop and field (or laboratory) welding shall be performed in like positions as would be required in a building application. All welding and inspection shall be performed by qualified personnel, and appropriate certification shall be submitted as part of the final documentation.

Additional details on fabrication and inspection are provided in the following appendices:

- Appendix A: **Guide Weld Procedure Specifications**
- Appendix B: **Guidelines for Welding Quality and Inspection**
- Appendix C: **Installation Procedures for High-Strength Bolts**

<u>Supplementary Test Specimens</u>

Beam-column connection testing projects which involve welded details shall fabricate at least two mock-up T-stub type weldment specimens for use by the Joining and Inspection team. These specimens shall be fabricated at the same time as the primary specimens by the same welders and using the same steel materials, welding processes, and inspection procedures. Details identical to those used for the complete beam-column connection shall be implemented. For example, if the connection has the back-up bars removed and the root passes back-gouged and rewelded, the same work should be performed on the T-stub specimens. Similarly, if the web of the beam prevents a continuous pass across the bottom flange weld, the mock-up specimen shall be fabricated with equivalent constraints. Details such as cover plates or other reinforcements shall also be incorporated in the T-stub specimens.

The supplementary weldment specimens shall be retained in the laboratory with the beam-column connections throughout the duration of the test program. If it is decided that these specimens will be tested by the Joining and Inspection team, arrangements for shipping (if necessary) will be made by SAC.

<u>Analytical Predictions</u>

The investigator is expected to perform a preliminary analysis of each specimen prior to testing to provide predictions of the specimen behavior and its ultimate failure mechanism. Such an analysis will also assist in finalizing the test protocol (including evaluating the adequacy of the loading apparatus) and the instrumentation plan. The analytical model should be sufficient to provide estimates of primary response parameters such as peak forces, displacements, and rotations to allow prediction of the required capabilities of the testing equipment (including force and displacement ranges), and specification of calibration limits for other instrumentation and prediction of likely behavior and failure modes. Material properties used in pre-test analyses should be based on coupon test data wherever possible.

Test Protocol

Prior to initiating testing, the investigator should develop a package of documentation which includes diagrams and a description of the test setup, an instrumentation plan, and a loading history. This initial package may be the used for all specimens tested in the series; notification shall be provided to SAC one week in advance of testing if any deviations from the submitted document are planned for a particular specimen. If unexpected circumstances develop during a test and no time is available to contact SAC personnel for a discussion of how to proceed, the investigator may alter the test program as he or she deems appropriate.

Submittal Requirements

Engineering drawings for the test apparatus and each test specimen shall be provided in advance of fabrication. Proposed WPS's shall also be provided at this time. For each specimen, an instrumentation plan and loading protocol must be submitted to SAC one week in advance of the start of testing. If there are no changes in the instrumentation or loading from the previous specimen, then no submittal is required. A summary of analyses to date, including any predictions of failure mechanism, should also be provided. This document should only be a few pages in length.

4. Test Set-Up

Instrumentation Plan

A basic instrumentation plan designed to ensure that consistent sets of data are produced in each series of beam-column connection tests is described in Appendix F. This instrumentation plan has been developed primarily for testing specimens representing interior or exterior beam-column connections along a single framing line. Installation details for various types of transducers are described, and provisions are included for bolted connections and composite specimens incorporating slabs. It is clear that modifications to the basic plan will be required for certain types of connections or when measurements of the behavior of a certain portion of a specimen are desired. Each investigator is required to develop their own basic instrumentation plan appropriate to the complete set specimens being tested in their program. This should be augmented with revised plans if any changes to the instrumentation are made prior to testing a particular specimen.

Connection Details and Restraints

Specimens may be tested in either a vertical or a horizontal configuration depending on the available laboratory attachments. However, the laboratory should have sufficient facilities such that all fabrication activities (such as welding beam-column connections or casting slabs) are representative of field conditions.

In most instances the primary load in the specimen will be applied via an actuator connected at a beam tip or a column tip; the remainder of the restraints will be assumed to be either pinned or roller-type connections. It is important that such restraints be properly designed to physically approximate the assumed boundary conditions. Out-of-plane restraints should be provided for tests of specimens in which the response in a single plane is desired. These may resist twisting or lateral torsional buckling of a beam or twisting in a column, or may be required to prevent damage to the loading apparatus. However, if at all possible, the presence of restraints should not prevent the specimen from developing behavior that is likely to occur in the field.

Other specialized test configurations, including tests of beam-column connection subcomponents, connections with imposed column axial load, or tests of complete frames or systems of frames, should be arranged in consultation with SAC.

Control System

Displacement signals may be manually controlled by the operator or may be pre-programmed command signals. In both cases, appropriate fail-safe displacement limits and shut-off procedures should be in place in case of loss of control. The majority of tests will be performed under displacement control; control displacement transducers should be located in parallel with the actuator but should be separate from the transducer on the actuator to avoid errors due to displacements in the clevis attachments. If load-controlled tests are performed (for example, to define the elastic slope of the loading curve up to some percentage of the analytically-predicted yield force), then a displacement limit must be set to avoid inadvertently damaging the specimen. In cases where multiple jacks are intended to be synchronous, the control equipment should be appropriate for multi-degree-of-freedom control.

Safety Issues

Lab personnel and observers should have sufficient protection and should remain a safe distance from the specimen at all times. Tests should be supervised by an individual experienced in large-scale structural testing. Care should be taken when marking, photographing, measuring, or otherwise inspecting the specimen any time the loading system is engaged, particularly when the specimen is subject to unstable behavior, e.g. at or near the peak of a loading cycle. The control system should have built-in fail-safe measures in case of loss of control.

Submittal Requirements

The basic instrumentation plan to be used for the complete test series shall be submitted for review one week prior to starting testing. Revised instrumentation plans for individual specimens shall be submitted as required, but no later than one week prior to testing the corresponding specimen. Prior to initiating the test program, the investigator must also submit drawings of the proposed test set-up, including the locations at which the load will be applied and details of other in-plane pinned or roller-type restraints. Components designed to prevent out-of-plane deformation in the specimen must be identified.

5. Test Documentation

The usefulness of the data acquired in any experimental program depends on the quality of the supporting documentation. This section outlines the types of information required as background material for any beam-column connection test, including material properties, specimen fabrication details, documentation of test set-up, presentation of instrumentation plan and loading plan, and documentation of observations during testing. Detailed information related to data processing, submissions, and archiving are given in the next section.

<u>Specimen Design and Fabrication</u>

Detailed documentation on the design, fabrication, and inspection of each specimen must be provided, including as-built drawings and fabrication and inspection reports. All specimen designs must be developed in conjunction with the Connection Performance team in the Phase 2 Steel Project, and fabrication and inspection must be undertaken by firms or individuals with experience in steel construction in seismic regions. The fabrication and inspection process should be supervised by the principal investigator in accordance with the requirements provided in Appendices B and C.

As-built engineering drawings should be produced for each specimen that indicate primary dimensions (or AISC designations) for all beam-column sections and supplemental steel materials (plates, bolts, etc.) in addition to welding details and any other information that would be required to reconstruct the as-built specimen. For composite construction, the connection details between the steel members and the concrete slab should be explicitly identified, as should the steel reinforcement in the slab itself. Variations from the details shown on the shop drawings should be noted.

All fabrication should be representative of conditions encountered in actual shop and field construction. The checklists provided in Appendix G should be completed for each specimen, and all other records related to the fabrication and inspection should be reported. In particular, correspondence with the fabricator, fabrication specifications, and any deviations from the specified WPS's and inspection procedures must be archived. Any repairs or rejectable defects left unrepaired in the specimen should be identified

<u>Material Properties</u>

Steel

All steel materials must be traceable in the sense that the supplier, heat number, and grade should be reported with the results of each material test. All mill certificates must also be saved and presented in the interim and final reports. Detailed material testing and reporting requirements are provided in Appendix D. Adherence to these requirements will ensure that the reported material properties are comparable with those determined in other testing and materials investigations.

Welding

All weld materials and processes and weld metal-base metal combinations must be consistent with those under evaluation by the Joining and Inspection team in the Phase 2 Steel Project to ensure that the as-built material properties are comparable with those determined by this team. Deviations from these materials or processes must be approved by SAC management prior to fabrication. The WPS's presented in Appendix A should be used as a guide for developing application-specific WPS's, depending on the thicknesses of the materials being joined and other conditions present in the connection. In all cases, the final welding parameters used in fabricating the specimen should be reported.

Reinforced Concrete

In any specimen constructed with a composite floor slab, the following information must be provided for the reinforced concrete:

- concrete mix design, including w/c ratio, maximum size of aggregate, and any additives
- concrete ultimate strength, f'_c, at 7 days, 14 days, 28 days, up to date of test (determined in accordance with ASTM C39)
- concrete stress-strain relationship at 28 days (recommended, not required)
- reinforcing steel: grade, yield and ultimate stress, plot of stress-strain curve

Other Materials

The fundamental mechanical properties of any other materials used in a beam-column connection specimen must be reported. This is particularly important for elements which are required to undergo substantial inelastic behavior or otherwise provide energy dissipation to a connection. Examples of important material properties include yield stress and strain of yielding materials, coefficient of friction in friction connections, or effective stiffness and damping of energy-dissipating materials. Specific reporting requirements for each particular material will be provided by SAC.

Instrumentation Plan

As described in Appendix F, a detailed instrumentation plan must be provided to SAC prior to starting a series of connection tests. However, it is recognized that additional instruments will likely be placed on particular specimens, perhaps even during the course of testing. This implies that additional documentation must be developed which clearly links the collected digital data with specific instruments and instrument locations; a preliminary revised instrumentation plan should be produced for each specimen one week before starting testing. Final instrumentation plans appropriate to each specimen must be included in the draft final report.

Documentation During Test

It is required that a written log be kept that records the progress of each test and notes significant observations, including initiation of yielding, buckling, or fracture. Any changes to the test set-up, and in particular any changes to the instrumentation (e.g. adding channels, changing instrument gains), should also be noted. Visual or auditory observations may be recorded. Most importantly, a description of the final failure (or deterioration) mechanism must be provided, along with diagrams or any photos of the critical regions of the specimen. The log should also note the condition of the test equipment and the laboratory, including the ambient temperature at the start of the test. If there are significant time delays between the completion of one cycle of loading and the initiation of the following cycles, the duration of the delay shall be noted. One copy of the test log must be submitted to SAC as part of the brief test report one week after the test is completed.

Numerous photographs and diagrams should be used to document the progress of each test. These photographs should include: close-ups of unique details prior to testing; an overall view of the specimen installed in the test machine; details of the connection at discrete peaks in the loading history showing any yielding (flaking of whitewash), local buckling, or other distress; and details of the failure region and failure surfaces (if applicable). These photographs should be well-documented to allow matching with particular instances in the loading history. In particular, at least one photograph should be taken at each level of applied displacement to support comparisons with behavior observed in actual buildings in post-earthquake inspections. If available, video should also be taken, particularly during the larger cycles of loading.

Submittal Requirements

Detailed design, fabrication, and inspection documentation must be kept for inclusion in the final report. Material properties and a revised instrumentation plan should also be compiled for each specimen and presented in the final report. A written log of the test should be submitted to SAC within one week after the test is completed.

6. Data Processing, Reporting, and Archiving

Preliminary Processing

All acquired data is expected to be processed to some extent before primary response quantities are calculated and results plotted. Smoothing or filtering routines used for this purpose should be detailed in both the final report and the data report. When multiple channels are averaged for calculation of primary response quantities, each of the individual channels used in taking the average should first be plotted separately and examined for unusual behavior. Any other assumptions made in processing the raw data should be clearly documented in the final report.

Primary Results

The basic response quantity that has been selected for evaluating the behavior of beam-column connections in the Phase 2 Steel Project is total interstory drift angle, denoted by θ. This quantity is different than the total plastic rotation which was used in the Phase 1 project because it also includes the elastic component: $\theta = \theta_e + \theta_p$. The definition of total drift angle for a beam-column connection specimen depends on whether the beam(s) or the column is being loaded (see Figs. 1 and 2):

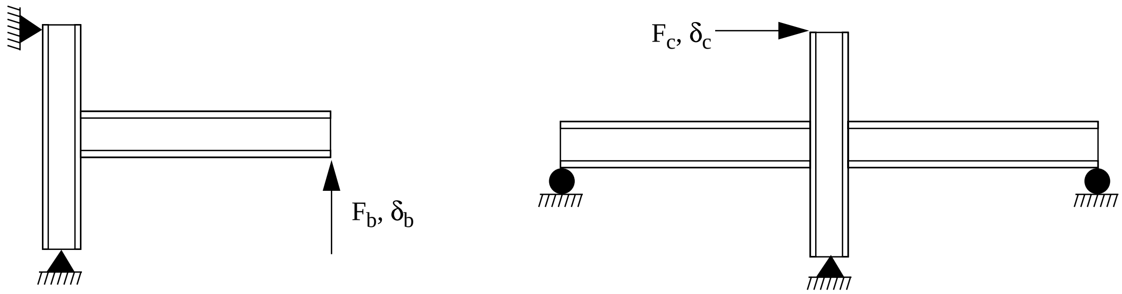
- if displacement is applied to the beam(s) while the column ends are pinned, then $\theta = \delta_b / L$
- if displacement is applied to the column while the beam ends are pinned, then $\theta = \delta_c / H$

where δ_b and δ_c are the applied beam and column tip displacements (including both elastic and inelastic components), respectively, L is the distance between the beam tip and the centerline of the column, and H is the distance from the point of load application for the column to the bottom. The points from which these dimensions are measured should have zero applied moment.

The total rotation is measured easily by displacement transducers at the point of load application. It can be broken into elastic and inelastic contributions from the beam, panel zone, and column. Proper instrumentation provides panel zone and column rotation angles (θ_{pz} and θ_{col}, respectively), but the beam rotation angle, θ_{beam}, must be derived from the other measured quantities. This is done by assuming that the displacement at the location of the applied load can be written as a sum:

$$\delta_b = \delta_{beam} + \delta_{pz} + \delta_{col} \text{ for displacement applied to the beam(s)}$$

$$\delta_c = \delta_{beam} + \delta_{pz} + \delta_{col} \text{ for displacement applied to the column}$$



Displacement applied to beam tip

Displacement applied to column tip

Figure 1. Possible Approaches for Loading Beam-Column Specimens

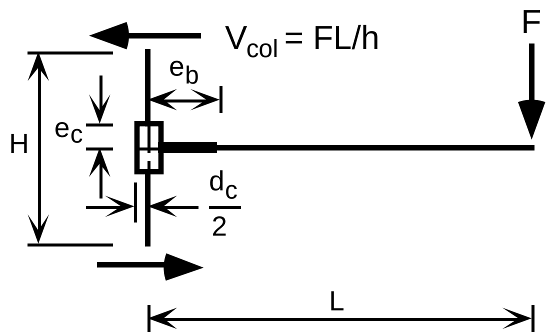


Figure 2. Definitions for a Beam-Column Specimen

The displacement quantities on the right-hand side of these equations represent the elastic and inelastic contributions from each element. From instrumentation and geometry δ_{pz} and δ_{col} are known. The contribution from the beam is then found by subtraction:

$$\delta_{beam} = \delta_b - \delta_{pz} - \delta_{col} \text{ for displacement applied to the beam(s)}$$

$$\delta_{beam} = \delta_c - \delta_{pz} - \delta_{col} \text{ for displacement applied to the column}$$

The beam rotation is then found by the relationship $\theta_{beam} = \delta_{beam}/L$. It is important to note that this beam rotation is not the rotation at the plastic hinge and it cannot be measured separately by instrumentation. If instrumentation is installed to measure rotations in the hinge region, this rotation should be referred to as the hinge rotation, θ_{hinge}, not the beam rotation.

As part of the preliminary test report, the following plots must be provided (where appropriate, these quantities should be plotted for each beam which frames into the column, or for the column itself):

- actuator force vs. beam tip displacement, or actuator force vs. column tip displacement
- moment at column centerline vs. θ
- moment at column centerline vs. θ_p, where θ_p is the inelastic component of the total interstory drift angle
- moment at column centerline vs. θ_{pz} if there is any inelastic action in the panel zone

The preliminary test report should also include:

- peak actuator force and beam tip displacement or column tip displacement
- θ_{max} and $\theta_{p, max}$
- θ_{pz}, θ_{col}, and θ_{beam} at the time θ_{max} was reached
- δ_{pz}, δ_{col}, and δ_{beam} at the time at which $\delta_{max, b \text{ or } c}$ was reached
- θ_{hinge}, if measured
- cumulative θ for excursions beyond the initial linear portion of the $M - \theta$ curve
- total energy dissipated (found by integrating the actuator force-displacement relationship)

Data Storage and Archiving

Immediately after completing each test, the acquired digital data should be backed up to a short-term storage device to provide redundancy of the data during the archiving process. All calibration files associated with the test should also be backed up with the scanned data. The investigator must keep copies of all documentation and data on a stable storage medium for a minimum of three years after completion of the test program.

Data Transfer

All raw digital data must be made available to SAC at the the time the draft final report is submitted. This data should be unprocessed and unsmoothed and provided in ASCII format in a single file of multiple data columns, each column corresponding to a single channel. It is preferred that the first column of the digital data is time, if it has been recorded in the test. The first 100 rows of each file should be reserved for information regarding the test, including the date, specimen ID, a description of the tests, the channel list, the units of the channels, and any comments on the data or the test results. All tests of the same specimen should be combined into this single file; if this requires zero correction of certain channels, then it may be performed but should be noted in the comments to the file. Any other preliminary processing should also be noted in the comments. Also, alterations to channels in the middle of a test (for example, due to a malfunctiion or an adjustment to the gain setting) should be reported.

Submittal Requirements

Within two weeks after completing tests of a specimen, a brief test report must be delivered to SAC which includes the written test log, basic force-displacement and moment-rotation plots, and preliminary conclusions. This report will be placed on the SAC WWW site for rapid dissemination to the engineering community.

Eight weeks after completing tests of a specimen, a draft Connection Test Summary report must be delivered to SAC. This will be reviewed, and a final version is due four weeks later.

All raw digital data must be made available to SAC at the completion of the testing program. The reduced dataset corresponding to the minimum channel list must also be supplied at this time.

7. Summary of Submittal Requirements

Deliverable	Delivered to SAC
Engineering drawings of proposed test apparatus; details of individual specimens; proposed WPS's*	1 week prior to starting fabrication
General instrumentation plan for test series*	1 week prior to starting test program
Detailed instrumentation plan (if different from initial instrumentation plan) and loading protocol (if different than SAC-specified loading protocol) for each specimen; summary of analyses and prediction of failure mechanism*	1 week prior to testing specimen
Brief test report, including written test log, sketch of connection detail, basic force-displacement and moment-rotation plots, and preliminary conclusions	2 weeks after testing specimen
Connection Test Summary, in standard SAC format	draft — 8 weeks after test final — 12 weeks after test
As-built drawings of specimen, fabrication and inspection reports, detailed material properties according to specification, final instrumentation plans, photographs and diagrams of specimen behavior	At submission of draft final report
Digital data in SAC format	At submission of draft final report

* These items will be reviewed by the SAC Project Director for Topical Investigations and other members of the Connection Performance team and other teams as appropriate. If no response is received within one week after submittal, this shall be interpreted as approval of the submitted information.