

PART VI
Appendix Q
Qualifying Cyclic Tests of Beam-to-Column and
Link-to-Column Connections

Q.1 Scope

This Appendix includes requirements for qualifying cyclic tests of beam-to-column moment connections in special and intermediate moment frames and link-to-column connections in eccentrically braced frames, when required in these Provisions. The purpose of the testing described in this Appendix is to provide evidence that a beam-to-column connection or a link-to-column connection satisfies the requirements for strength and interstory drift angle or link rotation angle in these Provisions. Alternative testing requirements are permitted when approved by the engineer of record and the authority having jurisdiction.

This Appendix provides minimum recommendations for simplified test conditions.

Q.2 Symbols

The numbers in parentheses after the definition of a symbol refers to the Section number in which the symbol is first used.

θ Interstory drift angle (Q.6)

γ_{total} Total link rotation angle (Q.6)

Q.3 Definitions

Complete loading cycle: A cycle of rotation taken from zero force to zero force, including one positive and one negative peak.

Interstory drift angle: Interstory displacement divided by story height, radians.

Inelastic rotation: The permanent or plastic portion of the rotation angle between a beam and the column or between a link and the column of the test specimen, measured in radians. The inelastic rotation shall be computed based on an analysis of test specimen deformations. Sources of inelastic rotation include yielding of members, yielding of connection elements and connectors, and slip between members and connection elements. For beam-to-column moment connections in special and intermediate moment frames, inelastic rotation is computed based upon the assumption that inelastic action is concentrated at a single point located at the intersection of the centerline of the beam with the centerline of the column. For link-to-column connections in eccentrically braced frames, inelastic rotation shall be computed based upon the assumption that inelastic action is concentrated at a single point located at the intersection of the centerline of the link with the face of the column.

Prototype : The connections, member sizes, steel properties, and other design, detailing, and construction features to be used in the actual building frame.

Test specimen : A portion of a frame used for laboratory testing, intended to model the prototype.

Test setup : The supporting fixtures, loading equipment, and lateral bracing used to support and load the test specimen.

Test subassemblage : The combination of the test specimen and pertinent portions of the test setup.

Total link rotation angle : The relative displacement of one end of the link with respect to the other end (measured transverse to the longitudinal axis of the undeformed link), divided by the link length. The total link rotation angle shall include both elastic and inelastic components of deformation of the link and the members attached to the link ends.

Q.4 Test Subassemblage Requirements

The test subassemblage shall replicate as closely as is practical the conditions that will occur in the prototype during earthquake loading. The test subassemblage shall include the following features :

- (1) The test specimen shall consist of at least a single column with beams or links attached to one or both sides of the column.
- (2) Points of inflection in the test assemblage shall coincide approximately with the anticipated points of inflection in the Prototype under earthquake loading.
- (3) Lateral bracing of the test subassemblage is permitted near load application or reaction points as needed to provide lateral stability of the test subassemblage. Additional lateral bracing of the test subassemblage is not permitted, unless it replicates lateral bracing to be used in the prototype.

Q.5 Essential Test Variables

The test specimen shall replicate as closely as is practical the pertinent design, detailing, construction features, and material properties of the prototype. The following variables shall be replicated in the test specimen.

Q.5.1 Sources of Inelastic Rotation

Inelastic rotation shall be developed in the test specimen by inelastic action in the same members and connection elements as anticipated in the prototype (in other words, in the beam or link, in the column panel zone, in the column outside of the panel zone, or in connection elements) within the limits described below. The percentage of the total inelastic rotation in the test specimen that is developed in each member or connection element shall be within 25 percent of the anticipated percentage of the total inelastic rotation in the prototype that is developed in the corresponding member or connection element.

Q.5.2 Size of Members

The size of the beam or link used in the test specimen shall be within the following limits:

- (1) The depth of the test beam or link shall be no less than 90 percent of the depth of the prototype beam or link.
- (2) The weight per foot of the test beam or link shall be no less than 75 percent of the weight per foot of the prototype beam or link.

The size of the column used in the test specimen shall properly represent the inelastic action in the column, as per the requirements in Section Q.5.1. In addition, the depth of the test column shall be no less than 90 percent of the depth of the prototype column.

Extrapolation beyond the limitations stated in this Section shall be permitted subject to qualified peer review and approval by the authority having jurisdiction.

Q.5.3 Connection Details

The connection details used in the test specimen shall represent the prototype connection details as closely as possible. The connection elements used in the test specimen shall be a full-scale representation of the connection elements used in the prototype, for the member sizes being tested.

Q.5.4 Continuity Plates

The size and connection details of continuity plates used in the test specimen shall be proportioned to match the size and connection details of continuity plates used in the prototype connection as closely as possible.

Q.5.5 Material Strength

The following additional requirements shall be satisfied for each member or connection element of the test specimen that supplies inelastic rotation by yielding:

- (1) The yield stress shall be determined by material tests on the actual materials used for the test specimen, as specified in Section Q.8. The use of yield stress values that are reported on certified mill test reports are not permitted to be used for purposes of this Section.

The yield stress of the beam shall not be more than 15 percent below R_y F_y for the grade of steel to be used for the corresponding elements of the prototype. Columns and connection elements with a tested yield stress shall not be more than 15 percent above or below R_y F_y for the grade of steel to be used for the corresponding elements of the prototype. R_y F_y shall be determined in accordance with Section Q.6.2.

Q.5.6 Welds

Welds on the test specimen shall satisfy the following requirements :

- (1) Welding shall be performed in strict conformance with Welding Procedure Specifications (WPS) as required in AWS D1.1. The WPS essential variables shall meet the requirements in AWS D1.1 and shall be within the parameters established by the filler-metal manufacturer. The tensile strength of the welds used in the tested assembly and the Charpy V-Notch (CVN) toughness used in the tested assembly shall be determined by material tests as specified in Section Q.8.3. The use of tensile strength and CVN toughness values that are reported on the manufacturer's typical certificate of conformance is not permitted to be used for purposes of this Section, unless the report includes results specific to Appendix T requirements.
- (2) The specified minimum tensile strength of the filler metal used for the test specimen shall be the same as that to be used for the corresponding prototype welds. The tested tensile strength of the test specimen weld shall not be more than 125 MPa above the tensile strength classification of the filler metal specification specified for the prototype.
- (3) The specified minimum CVN toughness of the filler metal used for the test specimen shall not exceed the specified minimum CVN toughness of the filler metal to be used for the corresponding prototype welds. The tested CVN toughness of the test specimen weld shall not be more than 50 percent, nor 34 kJ, whichever is greater, above the minimum CVN toughness that will be specified for the prototype.
- (4) The welding positions used to make the welds on the test specimen shall be the same as those to be used for the prototype welds.
- (5) Details of weld backing, weld tabs, access holes, and similar items used for the test specimen welds shall be the same as those to be used for the corresponding prototype welds. Weld backing and weld tabs shall not be removed from the test specimen welds unless the corresponding weld backing and weld tabs are removed from the prototype welds.
- (6) Methods of inspection and nondestructive testing and standards of acceptance used for test specimen welds shall be the same as those to be used for the prototype welds.

Q.5.7 Bolts

The bolted portions of the test specimen shall replicate the bolted portions of the prototype connection as closely as possible. Additionally, bolted portions of the test specimen shall satisfy the following requirements :

- (1) The bolt grade (for example, ASTM A325, A325M, ASTM A490, A490M, ASTM F1852) used in the test specimen shall be the same as that to be used for the prototype, except that ASTM A325 bolts may be substituted for ASTM F1852 bolts, and vice versa.

- (2) The type and orientation of bolt holes (standard, oversize, short slot, long slot, or other) used in the test specimen shall be the same as those to be used for the corresponding bolt holes in the prototype.
- (3) When inelastic rotation is to be developed either by yielding or by slip within a bolted portion of the connection, the method used to make the bolt holes (drilling, sub-punching and reaming, or other) in the test specimen shall be the same as that to be used in the corresponding bolt holes in the prototype.
- (4) Bolts in the test specimen shall have the same installation (pretensioned or other) and faying surface preparation (no specified slip resistance, Class A or B slip resistance, or other) as that to be used for the corresponding bolts in the prototype.

Q.6 LOADING HISTORY

Q.6.1 General Requirements

The test specimen shall be subjected to cyclic loads according to the requirements prescribed in Section Q.6.2 for beam-to-column moment connections in special and intermediate moment frames, and according to the requirements prescribed in Section Q.6.3 for link-to-column connections in eccentrically braced frames.

Loading sequences other than those specified in Sections Q.6.2 and Q.6.3 may be used when they are demonstrated to be of equivalent or greater severity.

Q.6.2 Loading Sequence for Beam-to-Column Moment Connections

Qualifying cyclic tests of beam-to-column moment connections in special and intermediate moment frames shall be conducted by controlling the interstory drift angle, θ , imposed on the test specimen, as specified below:

- (1) 6 cycles at $\theta = 0.00375$ rad
- (2) 6 cycles at $\theta = 0.005$ rad
- (3) 6 cycles at $\theta = 0.0075$ rad
- (4) 4 cycles at $\theta = 0.01$ rad
- (5) 2 cycles at $\theta = 0.015$ rad
- (6) 2 cycles at $\theta = 0.02$ rad
- (7) 2 cycles at $\theta = 0.03$ rad
- (8) 2 cycles at $\theta = 0.04$ rad

Continue loading at increments of $\theta = 0.01$ radian, with two cycles of loading at each step.

Q.6.3 Loading Sequence for Link-to-Column Connections

Qualifying cyclic tests of link-to-column moment connections in eccentrically braced frames shall be conducted by controlling the total link rotation angle, γ_{total} , imposed on the test specimen, as follows :

- (1) 6 cycles at $\gamma_{total} = 0.00375$ rad
- (2) 6 cycles at $\gamma_{total} = 0.005$ rad
- (3) 6 cycles at $\gamma_{total} = 0.0075$ rad
- (4) 6 cycles at $\gamma_{total} = 0.01$ rad
- (5) 4 cycles at $\gamma_{total} = 0.015$ rad
- (6) 4 cycles at $\gamma_{total} = 0.02$ rad
- (7) 2 cycles at $\gamma_{total} = 0.03$ rad
- (8) 1 cycle at $\gamma_{total} = 0.04$ rad
- (9) 1 cycle at $\gamma_{total} = 0.05$ rad
- (10) 1 cycle at $\gamma_{total} = 0.07$ rad
- (11) 1 cycle at $\gamma_{total} = 0.09$ rad

Continue loading at increments of $\gamma_{total} = 0.02$ radian, with one cycle of loading at each step.

Q.7 Instrumentation

Sufficient instrumentation shall be provided on the test specimen to permit measurement or calculation of the quantities listed in Section Q.9.

Q.8 Materials Testing Requirements**Q.8.1 Tension Testing Requirements for Structural Steel**

Tension testing shall be conducted on samples of steel taken from the material adjacent to each test specimen. Tension-test results from certified mill test reports shall be reported but are not permitted to be used in place of specimen testing for the purposes of this Section. Tension-test results shall be based upon testing that is conducted in accordance with Section Q.8.2. Tension testing shall be conducted and reported for the following portions of the test specimen:

- (1) Flange(s) and web(s) of beams and columns at standard locations
- (2) Any element of the connection that supplies inelastic rotation by yielding

Q.8.2 Methods of Tension Testing for Structural Steel

Tension testing shall be conducted in accordance with ASTM A6/A6M, ASTM A370, and ASTM E8, with the following exceptions:

- (1) The yield stress, F_y , that is reported from the test shall be based upon the yield strength definition in ASTM A370, using the offset method at 0.002 strain.
- (2) The loading rate for the tension test shall replicate, as closely as practical, the loading rate to be used for the test specimen.

Q.8.3 Weld Metal Testing Requirements

The tensile strength of the welds used in the tested assembly and the CVN toughness used in the tested assembly shall be determined by material tests as specified in Appendix T. The use of tensile strength and CVN toughness values that are reported on the manufacturer's typical certificate of conformance is not permitted to be used for purposes of this section, unless that report includes results specific to Appendix T requirements.

A single test plate may be used if the WPS for the test specimen welds is within plus/minus 0.8 kJ/mm of the WPS for the test plate.

Tensile specimens and CVN specimens shall be prepared in accordance with ANSI/AWS B4.0 Standard Methods for Mechanical Testing of Welds.

Q.9 Test Reporting Requirements

For each test specimen, a written test report meeting the requirements of the *authority having jurisdiction* and the requirements of this Section shall be prepared. The report shall thoroughly document all key features and results of the test. The report shall include the following information :

- (1) A drawing or clear description of the test subassembly, including key dimensions, boundary conditions at loading and reaction points, and location of lateral braces.
- (2) A drawing of the connection detail showing member sizes, grades of steel, the sizes of all connection elements, welding details including filler metal, the size and location of bolt holes, the size and grade of bolts, and all other pertinent details of the connection.
- (3) A listing of all other essential variables for the test specimen, as listed in Section Q.5.
- (4) A listing or plot showing the applied load or displacement history of the test specimen.
- (5) A listing of all demand critical welds.

- (6) Definition of the region of the connection that comprises the protected zones.
- (7) A plot of the applied load versus the displacement of the test specimen. The displacement reported in this plot shall be measured at or near the point of load application. The locations on the test specimen where the loads and displacements were measured shall be clearly indicated.
- (8) A plot of beam moment versus interstory drift angle for beam-to-column moment connections; or a plot of link shear force versus link rotation angle for link-to-column connections. For beam-to-column connections, the beam moment and the interstory drift angle shall be computed with respect to the centerline of the column.
- (9) The interstory drift angle and the total inelastic rotation developed by the test specimen. The components of the test specimen contributing to the total inelastic rotation due to yielding or slip shall be identified. The portion of the total inelastic rotation contributed by each component of the test specimen shall be reported. The method used to compute inelastic rotations shall be clearly shown.
- (10) A chronological listing of significant test observations, including observations of yielding, slip, instability, and fracture of any portion of the test specimen as applicable.
- (11) The controlling failure mode for the test specimen. If the test is terminated prior to failure, the reason for terminating the test shall be clearly indicated.
- (12) The results of the material tests specified in Section Q.8.
- (13) The Welding Procedure Specifications (WPS) and welding inspection reports.

Additional drawings, data, and discussion of the test specimen or test results are permitted to be included in the report.

Q.10 Acceptance Criteria

The test specimen must satisfy the strength and interstory drift angle or link rotation angle requirements of these Provisions for the special moment frame, intermediate moment frame, or eccentrically braced frame connection, as applicable. The test specimen must sustain the required interstory drift angle or link rotation angle for at least one complete loading cycle.

PART VI

Appendix R

Qualifying Cyclic Tests of Buckling-restrained Braces

R.1 Scope

This Appendix includes requirements for qualifying cyclic tests of individual buckling-restrained braces and buckling-restrained brace subassemblages, when required in these provisions. The purpose of the testing of individual braces is to provide evidence that a buckling-restrained brace satisfies the requirements for strength and inelastic deformation by these provisions; it also permits the determination of maximum brace forces for design of adjoining elements. The purpose of testing of the brace subassemblage is to provide evidence that the brace-design can satisfactorily accommodate the deformation and rotational demands associated with the design. Further, the subassemblage test is intended to demonstrate that the hysteretic behavior of the brace in the subassemblage is consistent with that of the individual brace elements tested uniaxially.

Alternative testing requirements are permitted when approved by the engineer of record and the authority having jurisdiction. This Appendix provides only minimum recommendations for simplified test conditions.

R.2 Symbols

The numbers in parentheses after the definition of a symbol refers to the Section number in which the symbol is first used.

- Δ_b Deformation quantity used to control loading of the test specimen (total brace end rotation for the subassemblage test specimen; total brace axial deformation for the brace test specimen) (Section R.6).
- $\Delta_{b,m}$ Value of deformation quantity, Δ_b , corresponding to the design story drift (Section R.6).
- $\Delta_{b,y}$ Value of deformation quantity, Δ_b , at first significant yield of test specimen (Section R.6).

R.3 Definitions

BRACE TEST SPECIMEN	A single buckling-restrained brace element used for laboratory testing intended to model the brace in the Prototype.
DESIGN METHODOLOGY	A set of step-by-step procedures, based on calculation or experiment, used to determine sizes, lengths, and details in the design of buckling-restrained braces and their connections.