Recommended Provisions for Buckling-Restrained Braced Frames

RAFAEL SABELLI

The following document has been developed to serve as a supplement to existing building codes in order to give guidance to design engineers wishing to employ buckling-restrained braced frames on projects in the United States, as well as to the building officials to whom such designs are submitted. It is expected that the *Recommended Provisions for Buckling-Restrained Braced Frames* will be included in the 2005 edition of the AISC *Seismic Provisions for Structural Steel Buildings*. All of the provisions presented here are currently under review in the draft of the 2005 *Seismic Provisions*. The provisions, as they are presented here, are suitable for use with the 2002 *Seismic Provisions for Structural Steel Buildings* (AISC, 2002), hereafter referred to as the *Seismic Provisions*, and include references to other sections of those provisions throughout. Therefore, consistent with the 2002 *Seismic Provisions*, LRFD format is used.

This relatively new seismic-load-resisting system, more fully described in Lopez, Gwie, Lauck, and Saunders (2004), transcends many of the performance and ductility limitations associated with concentrically braced frames. This being the case, it is a natural candidate for consideration for project types that have traditionally included braced frames, and in order for such consideration to be given, a reliable design method and a consensus on design and testing requirements is necessary. The *Recommended Provisions for Buckling-Restrained Braced Frames*, hereafter referred to as *Recommended Provisions*, represent a five-year effort in which AISC and the Structural Engineers Association of California collaborated to create a set of guidelines that is both practical and sufficiently rigorous to ensure a level of reliability at least as that provided by other seismic-load-resisting systems.

The main body of the *Recommended Provisions* consists of sections that would be included in the AISC *Seismic Provisions* (AISC, 2002), to address buckling-restrained braced frames. These include a section of provisions that outline detailing and strength requirements for elements of the system. These provisions are presented as a new Section 16, displacing the current Section 16 of the *Seismic Provisions* (Quality Assurance). The *Recommended Provisions* also include an appendix on the testing required to qualify buckling-restrained brace designs for use. This appendix (Appendix T) includes testing requirements (such as brace similitude, extrapolation limits, and testing protocol), as well as the acceptance criteria. Commentaries corresponding to Section 16 and Appendix T are also presented.

Because the current edition of SEI/ASCE 7, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2002), does not include buckling-restrained braced frames, additional design coefficients are presented in the *Recommended Provisions*. The required building code coefficients (the Response Modification Coefficient, the System Overstrength Factor, and the Deflection Amplification Factor), along with height limits for different seismic design categories, and the coefficients required for an approximation of building period, are presented in an Appendix R to the *Seismic Provisions*; this appendix is expected to be used only until ASCE 7 addresses buckling-restrained braced frames.

Similar provisions have been included in FEMA 450, 2003 *NEHRP Recommended Provisions for New Buildings and Other Structures* (FEMA, 2003). The differences are few, but it is recommended that these provisions be used rather than those in FEMA 450 as they have benefited from the continuing analytical and experimental research on the system.

Participants in the development of the *Recommended Provisions* included Ian Aiken, Walterio López, Kevin Moore, Badri Prasad, Mark Sinclair, Greg Deierlein, Subhash Goel, Bob Lyons, Peter Maranian, Eduardo Miranda, Egor Popov, Mark Saunders, Bozidar Stojadinovic, and the author. Additional support was provided by James O. Malley, Chair of the AISC Task Committee 9 on Seismic Design, and Douglas C. Hohbach, Chair of the Seismology Committee of the Structural Engineers Association of California. Professors Stephen Mahin and Robert Tremblay provided valuable assistance. The development of the *Recommended Provisions* was also aided by analytical research funded by a fellowship from the Earthquake Engineering Research Institute and the Federal Emergency Management Agency's National Earthquake Hazard Reduction Program.

Rafael Sabelli is senior associate, Dasse Design Inc., San Francisco.

THE RECOMMENDED PROVISIONS

Symbols

A_{sc}	Area of the yielding segment of steel core, in.^{2} (mm^2)
P_{ysc}	Axial yield strength of steel core, kips (N)
β	Compression strength adjustment factor
ω	Tension strength adjustment factor

Glossary

Adjusted brace strength (BRBF). Strength of a brace in a buckling-restrained braced frame at deformations corresponding to 2.0 times the design story drift.

Buckling-restrained braced frame (BRBF). Diagonally braced frame meeting the requirements of Section 16 in which all members of the bracing system are subjected primarily to axial forces and in which the limit state of compression buckling of braces is precluded at forces and deformations corresponding to 2.0 times the design story drift.

Buckling-restraining system. System of restraints that limits buckling of the steel core in BRBF. This system includes the casing on the steel core and structural elements adjoining its connections. The buckling-restraining system is intended to permit the transverse expansion and longitudinal contraction of the steel core for deformations corresponding to 2.0 times the design story drift.

Casing. Element that resists forces transverse to the axis of the brace thereby restraining buckling of the core. The casing requires a means of delivering this force to the remainder of the buckling-restraining system. The casing resists little or no force in the axis of the brace.

Steel core. Axial-force-resisting element of braces in BRBF. The steel core contains a yielding segment and connections to transfer its axial force to adjoining elements; it may also contain projections beyond the casing and transition segments between the projections and yielding segment.

Section 16. Buckling-Restrained Braced Frames (BRBF)

16.1. Scope

Buckling-Restrained Braced Frames (BRBF) are expected to withstand significant inelastic deformations when subjected to the forces resulting from the motions of the Design Earthquake. BRBF shall meet the requirements in this Section. Where the applicable building code does not contain design coefficients for BRBF, the provisions of Appendix R shall apply.

16.2. Bracing Members

16.2a. Composition

Bracing members shall be composed of a structural steel core and a system that restrains the steel core from buckling.

16.2a.1. Steel Core

The steel core shall be designed to resist the entire axial force in the brace.

16.2a.1.a. Required Strength of Steel Core

The required axial strength of the brace shall not exceed the design strength of the steel core, ϕP_{ysc}:

where

ϕ = 0.90

$$P_{ysc} = F_y A_{sc} \tag{16-1}$$

F_y = specified minimum yield stress of steel core

A_{sc} = net area of steel core

16.2a.1.b. Detailing

16.2a.1.b.1. Plates used in the steel core that are 2 in. (50 mm) thick or greater shall satisfy the minimum notch toughness requirements of Section 6.3 of the *Seismic Provisions*.

16.2a.1.b.2. Splices in the steel core are not permitted.

16.2a.2. Buckling-Restraining System

The buckling-restraining system shall consist of the casing for the steel core. In stability calculations, beams, columns, and gussets connecting the core shall be considered parts of this system.

The buckling-restraining system shall limit local and overall buckling of the steel core for deformations corresponding to 2.0 times the design story drift. The buckling-restraining system shall not be permitted to buckle within deformations corresponding to 2.0 times the design story drift.

16.2b. Testing

The design of braces shall be based upon results from qualifying cyclic tests in accordance with the procedures and acceptance criteria of Appendix T. Qualifying test results shall consist of at least two successful cyclic tests: one is required to be a test of a brace subassemblage that includes brace connection rotational demands complying with Appendix T4 and the other shall be either a uniaxial or a subassemblage test complying with Appendix T5. Both test types are permitted to be based upon one of the following:

16.2b.1. Types of Qualifying Tests

16.2b.1.a. Tests reported in research or documented tests performed for other projects that reasonably match project conditions.

16.2b.1.b. Tests that are conducted specifically for the project and are representative of project member sizes, material strengths, brace-end connection configurations, and matching assembly and quality control processes.

16.2b.2. Applicability

Interpolation or extrapolation of test results for different member sizes shall be justified by rational analysis that demonstrates stress distributions and magnitudes of internal strains that are consistent with or less severe than the tested assemblies and that considers the adverse effects of larger material and variations in material properties. Extrapolation of test results shall be based upon similar combinations of steel core and buckling-restraining system sizes. Tests shall be permitted to qualify a design when the provisions of Appendix T are met.

16.2b.3. Adjusted Brace Strength

Adjusted Brace Strength: The Adjusted Brace Strength in compression shall be $\beta\omega R_y P_{ysc}$. The Adjusted Brace Strength in tension shall be $\omega R_y P_{ysc}$.

Exception: The factor R_y need not be applied if P_{ysc} is established using yield stress determined from a coupon test.

16.2b.3.a. Compression Strength Adjustment Factor (β) shall be calculated as the ratio of the maximum compression force to the maximum tension force of the test specimen measured from the qualification tests specified in Appendix T6.3 for the range of deformations corresponding to 2.0 times the design story drift. The larger value of β from the two required brace qualification tests shall be used. In no case shall β be taken as less than 1.0.

16.2b.3.b. Tension Strength Adjustment Factor (ω) shall be calculated as the ratio of the maximum tension force measured from the qualification tests specified in Appendix T6.3 (for the range of deformations corresponding to 2.0 times the design story drift) to the nominal yield strength of the test specimen. The larger value of ω from the two required qualification tests shall be used. Where the tested steel core material does not match that of the prototype, ω shall be based on coupon testing of the prototype material.

16.3. Bracing Connections

16.3a. Required Strength

The required strength of bracing connections in tension and compression (including beam-to-column connections if part of the bracing system) shall be 1.1 times the adjusted brace strength in compression.

16.3b. Gusset Plates

The design of connections shall include considerations of local and overall buckling. Bracing consistent with that used in the tests upon which the design is based is required.

User Note:
This provision may be met by designing the gusset plate for a transverse force consistent with transverse bracing forces determined from testing, by adding a stiffener to it to resist this force, or providing a brace to the gusset plate or to the brace itself. Where the supporting tests did not include transverse bracing, no such bracing is required. Any attachment of bracing to the steel core must be included in the qualification testing.

16.4. Special Requirements Related to Bracing Configuration

16.4a. V-Type and Inverted-V-Type Bracing

V-type and inverted-V-type braced frames shall meet the following requirements:

16.4a.1. Required Strength

The required strength of members and connections shall be determined based on the load combinations of the Applicable Building Code assuming that the braces provide no support of

TABLE I-8-1

Limiting Width-Thickness Ratios λ_{ps} for Compression Elements

Description of Element		Width Thickness Ratio	Limiting Width-Thickness Ratios
			λ_{ps} (seismically compact)
Unstiffened Elements	Flanges of I-shaped rolled, hybrid or welded beams and columns	b/t	$0.30\sqrt{E/F_y}$
Stiffened Elements	Webs in flexural compression or combined flexure and axial compression	h/t_w	for $C_a \le 0.125$ [i] $3.14\sqrt{\frac{E}{F_y}}\left(1-1.54C_a\right)$ for $C_a > 0.125$ [i] $1.12\sqrt{\frac{E}{F_y}}\left(2.33-C_a\right)\ge 1.49\sqrt{\frac{E}{F_y}}$

[i] where

$C_a = P_u/(\phi_b P_y)$

P_u = required axial compression strength (LRFD), kips (N)

P_y = yield strength, kips (N)

ϕ_b = 0.90

dead and live loads. For load combinations that include earthquake effects, the vertical and horizontal earthquake effect (E) on the beam shall be determined from the adjusted brace strengths in tension and compression.

16.4a.2. Beam Requirements

Beams shall be continuous between columns. Both flanges of beams shall be laterally braced. Lateral braces shall meet the provisions of Equations C3-9 and C3-10 of the *LRFD Specification for Structural Steel Buildings* (AISC, 1999), where $C_d = 1.0$. As a minimum, one set of lateral braces is required at the point of intersection of the V-type (or inverted V-type) bracing, unless the beam has sufficient out-of-plane strength and stiffness to ensure stability between adjacent brace points.

User Note:
The beam has sufficient out-of-plane strength and stiffness if the beam bent in the horizontal plane meets the required brace strength and required brace stiffness for column nodal bracing as prescribed in the Specification. P_u shall be taken as the required compressive strength of the brace.

16.4a.3. Brace Deformation

For the purposes of brace design and testing, the calculated maximum deformation of braces shall be increased by including the effect of the vertical deflection of the beam under the loading defined in 16.4a.1.

16.4b. K-Type Bracing

K-type braced frames are not permitted for BRBF.

16.5. Columns

Columns in BRBF shall meet the following requirements:

16.5a. Width-thickness Ratios

Compression elements of columns shall satisfy the width-thickness limitations in Table I-8-1.

16.5b. Splices

In addition to meeting the requirements in Section 8.3 of the *Seismic Provisions*, column splices in BRBF shall be designed to develop at least the available shear strength of the smaller connected member and 50 percent of the available flexural strength of the smaller connected member determined based on the limit state of yielding. Splices shall be located in the middle one-third of the column clear height.

16.5c. Required Strength

In addition to the requirements in Section 8.3 of the *Seismic Provisions*, the required strength of columns in BRBF shall be determined from load combinations as stipulated in the applicable building code. For load combinations that include the amplified seismic load, the amplified earthquake effect ($\Omega_o E$) on the column shall be determined from the adjusted brace strengths in tension and compression.

The required column strength need not exceed the maximum force that can be delivered by the system.

16.6. Beams

Beams in BRBF shall meet the following requirements:

16.6a. Width-thickness Ratios

Compression elements of beams shall satisfy the width-thickness limitations in Table I-8-1.

16.6b. Required Strength

For load combinations that include earthquake effects, the earthquake effect (E) on the beam shall be determined from the adjusted brace strengths in tension and compression.

This earthquake effect need not be considered for load combinations that include the amplified seismic load.

Appendix R. Seismic Design Coefficients and Approximate Period Parameters

R1. Scope

This Appendix contains design coefficients, system limitations and design parameters for seismic load resisting systems (SLRS) that are included in these provisions but not yet defined in the applicable building code (ABC): Buckling-Restrained Braced Frames (BRBF). The values presented in Tables R1-1 and R1-2 in this Appendix shall only be used where neither the ABC nor ASCE 7 contain such values.

User Note:
The design coefficients and parameters presented in this Appendix are taken from the 2003 NEHRP *Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*. This Appendix will be deleted from these Provisions once ASCE 7 and the Applicable Building Codes add the BRBF and Special Plate Shear Wall to their list of acceptable structural systems. It is expected that such parameters will be included in an Appendix to ASCE 7 which is expected to be published in mid to late 2005.

R2. Symbols

The following symbols are used in this Appendix.

C_d	Deflection amplification factor
C_r, x	Parameters used for determining the approximate fundamental period
Ω_o	System overstrength factor

R3. Design Coefficients and Factors for Basic Seismic Load Resisting Systems

Table R3-1.
Design Coefficients and Factors for Basic Seismic Load Resisting Systems

Basic Seismic Load-Resisting System	**Response Modification Coefficient** R	**System Overstrength Factor** Ω_o	**Deflection Amplification Factor** C_d	**Height Limit (ft)**			
				Seismic Design Category			
				B & C	D	E	F
Building Frame Systems							
Buckling-Restrained Braced Frames, non-moment-resisting beam-column connections	7	2	5½	NL	160	160	100
Buckling-Restrained Braced Frames, moment-resisting beam-column connections	8	2½	5	NL	160	160	100
Dual Systems with Special Moment Frames Capable of Resisting at Least 25% of the Prescribed Seismic Forces							
Buckling-Restrained Braced Frame	8	2½	5	NL	NL	NL	NL

(NL = Not Limited)

User Note:
The values in this table are intended to be used in the same ways as those in Table 9.5.2.2 of ASCE 7-02 (ASCE, 2002).

R4. Values of Approximate Period Parameters

Table R4-2.
Values of Approximate Period Parameters C_r and x

Structure Type	C_r	x
Buckling-Restrained Braced Frames	0.03	0.75

User Note:
The values in this table are intended to be used in the same ways as those in Table 9.5.5.3.2 of ASCE 7-02.

Appendix T. Qualifying Cyclic Tests of Buckling-Restrained Braces

T1. Scope and Purpose

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 in 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 regulatory agency.

This Appendix provides only minimum recommendations for simplified test conditions.

T2. Symbols

Δ_b	Deformation quantity used to control loading of test specimen (total brace end rotation for the subassemblage test specimen; total brace axial deformation for the Brace Test Specimen).
Δ_{bm}	Value of deformation quantity, Δ_b, corresponding to the design story drift.
Δ_{by}	Value of deformation quantity, Δ_b, at first significant yield of test specimen.

T3. Glossary

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.

Inelastic deformation. The permanent or plastic portion of the axial displacement in a buckling-restrained brace, divided by the length of the yielding portion of the brace, expressed in percent.

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

Subassemblage test specimen. The combination of the brace, the connections and testing apparatus that replicate as closely as practical the axial and flexural deformations of the brace in the Prototype.

Test specimen. Brace Test Specimen or subassemblage test specimen.

T4. Subassemblage Test Specimen

The subassemblage test specimen shall satisfy the following requirements:

1. The mechanism for accommodating inelastic curvature in the subassemblage test specimen brace shall be the same as that of the prototype. The rotational deformation demands on the subassemblage test specimen brace shall be equal to or greater than those of the prototype.
2. The axial yield strength of the steel core (P_{ysc}) of the brace in the subassemblage test specimen shall not be less than of that of the prototype as determined from coupon test.
3. The cross-sectional shape and orientation of the steel core projection of the subassemblage test specimen brace shall be the same as that of the brace in the prototype.
4. The same documented design methodology shall be used for design of the subassemblage as used for the prototype, to allow comparison of the rotational deformation demands on the subassemblage brace to the prototype.
5. The calculated margins of safety for the prototype connection design, steel core projection stability, overall buckling and other relevant subassemblage test specimen brace construction details, excluding the gusset plate, for the prototype, shall equal or exceed those of the subassemblage test specimen construction.

6. Lateral bracing of the subassemblage test specimen shall replicate the lateral bracing in the prototype.
7. Manufacture of brace test specimen: The brace test specimen and the prototype shall be manufactured in accordance with the same quality control and assurance processes and procedures.

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

T5. Brace Test Specimen

The Brace Test Specimen shall replicate as closely as is practical the pertinent design, detailing, construction features, and material properties of the Prototype.

T5.1. Design of Brace Test Specimen

The same documented design methodology shall be used for the Brace Test Specimen and the Prototype. The design calculations shall demonstrate, at a minimum, the following requirements:

1. The calculated margin of safety for stability against overall buckling for the prototype shall equal or exceed that of the brace test specimen.
2. The calculated margins of safety for the brace test specimen and the prototype shall account for differences in material properties, including yield and ultimate stress, ultimate elongation, and toughness.

T5.2. Manufacture of Brace Test Specimen

The brace test Specimen and the prototype shall be manufactured in accordance with the same quality control and assurance processes and procedures.

T5.3. Similarity of Brace Test Specimen and Prototype

The brace test specimen shall meet the following requirements:

1. The cross-sectional shape and orientation of the steel core shall be the same as that of the prototype.
2. The axial yield strength of the steel core (P_{ysc}) of the brace test specimen shall not vary by more than 50 percent from that of the prototype as determined from coupon tests.
3. The material for, and method of, separation between the steel core and the buckling restraining mechanism in the brace test specimen shall be the same as that in the prototype.

Extrapolation beyond the limitations stated in this section shall be permitted subject to qualified peer review and building official approval.

T5.4. Connection Details

The connection details used in the brace test specimen shall represent the prototype connection details as closely as practical.

T5.5. Materials

1. Steel Core: The following requirements shall be satisfied for the steel core of the brace test specimen:
   a. The nominal yield stress of the prototype steel core shall be the same as that of the brace test specimen.
   b. The yield strength of the material of the steel core in the prototype shall not exceed 110 percent of that of the brace test specimen as determined from coupon tests.
   c. The specified minimum ultimate stress and strain of the prototype steel core shall meet or exceed those of the brace test specimen.
2. Buckling-Restraining Mechanism
   Materials used in the buckling-restraining mechanism of the brace test specimen shall be the same as those used in the Prototype.

T5.6. Connections

The weld, bolted, and pinned joints on the test specimen shall replicate those on the prototype as close as practical.

T6. Loading History

T6.1. General Requirements

The test specimen shall be subjected to cyclic loads according to the requirements prescribed on Sections T6.2 and T6.3. Additional increments of loading beyond those described in Section T6.3 are permitted. Each cycle shall include a full tension and full compression excursion to the prescribed deformation.

T6.2. Test Control

The test shall be conducted by controlling the level of axial or rotational deformation (Δ_b) imposed on the Test Specimen. As an alternate, the maximum rotational deformation may be applied and maintained as the protocol is followed for axial deformation.

T6.3. Loading Sequence

Loads shall be applied to the test specimen to produce the following deformations, where the deformation is the steel core axial deformation for the test specimen and the rotational deformation demand for the subassemblage test specimen brace:

1. 2 cycles of loading at the deformation corresponding to $\Delta_b = \Delta_{by}$
2. 2 cycles of loading at the deformation corresponding to $\Delta_b = 0.50\ \Delta_{bm}$
3. 2 cycles of loading at the deformation corresponding to $\Delta_b = 1\ \Delta_{bm}$
4. 2 cycles of loading at the deformation corresponding to $\Delta_b = 1.5\ \Delta_{bm}$
5. 2 cycles of loading at the deformation corresponding to $\Delta_b = 2.0\ \Delta_{bm}$.
6. Additional complete cycles of loading at the deformation corresponding to $\Delta_b = 1.5\ \Delta_{bm}$ as required for the Brace Test Specimen to achieve a cumulative inelastic axial deformation of at least 200 times the yield deformation (not required for the subassemblage test specimen).

The design story drift shall not be taken as less than 0.01 times the story height for the purposes of calculating Δ_{bm}. Other loading sequences are permitted to be used to qualify the test specimen when they are demonstrated to be of equal or greater severity in terms of maximum and cumulative inelastic deformation.

T7. Instrumentation

Sufficient instrumentation shall be provided on the test specimen to permit measurement or calculation of the quantities listed in Appendix T9.

T8. Materials Testing Requirements

T8.1. Tension Testing Requirements

Tension testing shall be conducted on samples of steel taken from the same material as that used to manufacture the steel core. 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 T8.2.

T8.2. Methods of Tension Testing

Tension testing shall be conducted in accordance with ASTM A6, 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 of 0.002 strain.
2. The loading rate for the tension test shall replicate, as closely as is practical, the loading rate used for the test specimen.
3. The coupon shall be tested in the axis in which the steel core in the test Specimen will be loaded.

T9. Test Reporting Requirements

For each Test Specimen, a written test report meeting 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 Specimen, including key dimensions, boundary conditions at loading and reaction points, and location of lateral bracing, if any.
2. A drawing of the connection details showing member sizes, grades of steel, the sizes of all connection elements, welding details including filler metal, the size and location of bolt or pin holes, the size and grade of connectors, and all other pertinent details of the connections.
3. A listing of all other essential variables as listed in Section T4 or T5 as appropriate.
4. A listing or plot showing the applied load or displacement history.
5. A plot of the applied load versus the deformation (Δ_b). The method used to determine the deformations shall be clearly shown. The locations on the Test Specimen where the loads and deformations were measured shall be clearly identified.

6. A chronological listing of significant test observations, including observations of yielding, slip, instability, transverse displacement along the Test Specimen and fracture of any portion of the Test Specimen and connections, as applicable.
7. The results of the material tests specified in Section T8.
8. The manufacturing quality-control and quality-assurance plans used for the fabrication of the Test Specimen. These shall be included with the Welding Procedure Specifications and welding inspection reports.

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

T10. Acceptance Criteria

At least one subassemblage test shall be performed to satisfy the requirements of Section T4. At least one brace test shall be performed to satisfy the requirements of Section T5. Within the required protocol range, all tests shall satisfy the following requirements:

1. The plot showing the applied load vs. displacement history shall exhibit stable, repeatable behavior with positive incremental stiffness.
2. There shall be no fracture, brace instability or brace end connection failure.
3. For brace tests, each cycle to a deformation greater than Δ_{by}, and the maximum tension and compression forces shall not be less than 1.0 P_{ysc}.
4. For brace tests, each cycle to a deformation greater than Δ_{by}, and the ratio of the maximum compression force to the maximum tension force shall not exceed 1.3.

Other acceptance criteria may be adopted for the brace test specimen or subassemblage test specimen subject to qualified peer review and approval by the AHJ.

Commentary C16. Buckling-Restrained Braced Frames (BRBF)

C16.1. Scope

Buckling-restrained braced frames are a special class of concentrically braced frames. Just as in Special Concentrically Braced Frames (SCBF), the centerlines of BRBF members that meet at a joint intersect at a point to form a complete vertical truss system that resists lateral forces. BRBF have more ductility and energy absorption than SCBFs because overall brace buckling, and its associated strength degradation, is precluded at forces and deformations corresponding to the design story drift. See Sections 13 and 14 for the effects of buckling in SCBF. Figure C-I-13.1 of the *Seismic Provisions* Commentary shows possible BRBF bracing configurations; note that neither X-bracing nor K-bracing is an option for BRBF.

BRBF are characterized by the ability of bracing elements to yield inelastically in compression as well as in tension. In BRBF the bracing elements dissipate energy through stable tension-compression yield cycles (Clark, Aiken, Kasai, Ko, and Kimura, 1999). Figure C-I-16.2 shows the characteristic hysteretic behavior for this type of brace as compared to that of a buckling brace. This behavior is achieved through limiting buckling of the steel core within the bracing elements. Axial stress is de-coupled from flexural buckling resistance; axial load is confined to the steel core while the buckling restraining mechanism, typically a casing, resists overall brace buckling and restrains high-mode steel core buckling (rippling).

Buckling-restrained braced frames are composed of columns, beams, and bracing elements, all of which are subjected primarily to axial forces. Braces of BRBF are composed of a steel core and a buckling-restraining system encasing the steel core. Figure C-I-16.1 shows a schematic of BRBF bracing element (adapted from Tremblay, Degrange, and Blouin, 1999). More examples of BRBF bracing elements are found in Watanabe, Hitomi, Saeki, Wada, and Fujimoto, 1988; Wada, Connor, Kawai, Iwata, and Watanabe (1994); and Clark and others (1999). The steel core within the bracing element is intended to be the primary source of energy dissipation. During a moderate to severe earthquake the steel core is expected to undergo significant inelastic deformations.

BRBF can provide elastic stiffness that is comparable to that of EBF or SCBF. Full-scale laboratory tests indicate that properly designed and detailed bracing elements of BRBF exhibit symmetrical and stable hysteretic behavior under tensile and compressive forces through significant inelastic deformations (Watanabe and others, 1988; Wada, Saeki, Takeuchi, and Watanabe, 1998; Clark and others, 1999; Tremblay and others, 1999). The ductility and energy dissipation capability of BRBF is expected to be comparable to that of SMF and greater than that of SCBF. This high ductility is attained by limiting buckling of the steel core.

The axial yield strength of the core, P_{ysc}, can be defined without dependence on other variables. This ability to control P_{ysc} significantly reduces the adverse effects of relying on nominal yield strength values. Careful proportioning of braces throughout the building height can result in specification of required P_{ysc} values that meet all of the strength and drift requirements of the applicable building code.

These provisions are based on the use of brace designs qualified by testing. They are intended to ensure that braces are used only within their proven range of deformation capacity, and that yield and failure modes other than stable brace yielding are precluded at the maximum inelastic drifts corresponding to the design earthquake. For analyses performed using linear methods, the maximum inelastic drifts for this system are defined as those corresponding to 200 percent of the design story drift. For nonlinear time-history analyses, the maximum inelastic drifts can be taken directly from the analyses results. This approach is consistent with the linear analysis equations for design story drift in the 1997 *Uniform Building Code* (ICBO, 1997) and the 2000 *NEHRP Recommended Provisions* (FEMA, 2000). It is also noted that the consequences of loss of connection stability due to the actual seismic displacements exceeding the calculated values may be severe; braces are therefore required to have a larger deformation capacity than directly indicated by linear static analysis.

Although this system has not been included in ASCE 7 (ASCE, 2002), these provisions have been written assuming that future editions of ASCE 7 and of national codes will define system coefficients and limits for Buckling-Restrained Braced Frames. The assumed values for the response modification coefficient, system overstrength factor, and deflection amplification factor are given in Appendix R, as are height limits and period-calculation coefficients.

The design engineer utilizing these provisions is strongly encouraged to consider the effects of configuration and proportioning of braces on the potential formation of building yield mechanisms. It is also recommended that engineers refer to the following documents to

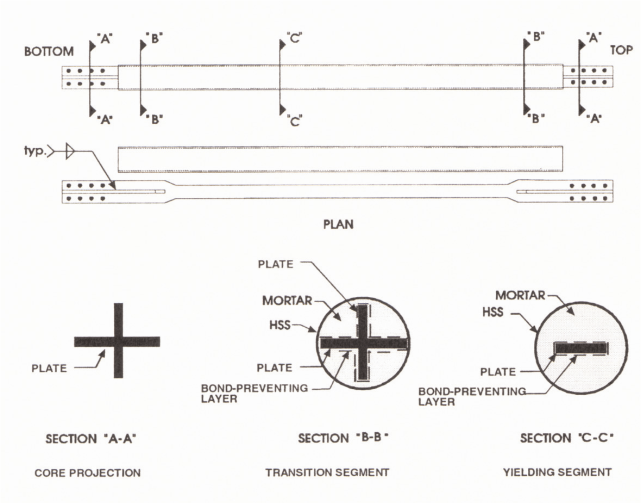


Fig. C-I-16.1. Details of a Buckling-Restrained Brace (Courtesy of R. Tremblay).

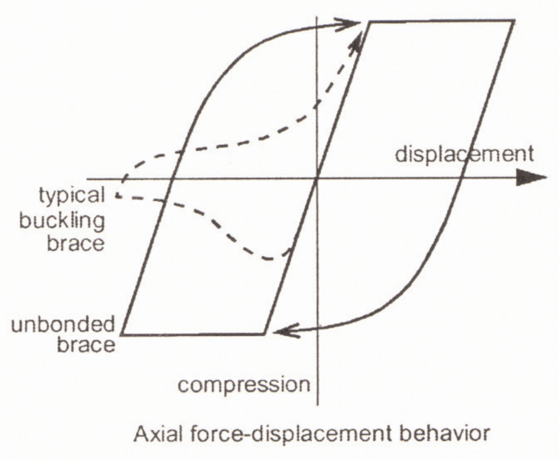


Fig. C-I-16.2. Buckling-Restrained (Unbonded) Brace Hysteretic Behavior (Courtesy of Seismic Isolation Engineering).

gain further understanding of this system: Watanabe and others (1988), Reina and Normile (1997), Clark and others (1999), Tremblay and others (1999), and Kalyanaraman, Sridhara, and Thairani (1998).

During the planning stages of either a subassemblage or uniaxial brace test, certain conditions may exist that cause the Test Specimen to deviate from the parameters established in the testing appendix. These conditions may include:

- Availability of beam, column, and brace sizes that reasonably match those to be used in the actual building frame
- Test set-up limitations in the laboratory
- Actuator and reaction-block capacity of the laboratory
- Transportation and field-erection constraints
- Actuator to subassemblage connection conditions that require reinforcement of test specimen elements not reinforced in the actual building frame

In certain cases, both building official and qualified peer reviewer may deem such deviations acceptable. The cases in which such deviations are acceptable are project-specific by nature and, therefore, do not lend themselves to further description in this Commentary. For these specific cases, it is recommended that the engineer of record demonstrate that the following objectives are met:

- reasonable relationship of scale
- similar design methodology
- adequate system strength
- stable buckling-restraint of the steel core
- adequate rotation capacity
- adequate cumulative strain capacity

The design provisions for BRBF's are predicated on reliable brace performance. In order to assure this performance, a Quality Assurance Plan is required. These measures are in addition to those covered in the AISC *Code of Standard Practice* (AISC, 2000) and Section 16 of the 2002 AISC *Seismic Provisions*. Examples of measures that may provide quality assurance are:

- Special inspection of brace fabrication.
- Inspection may include confirmation of fabrication and alignment tolerances, as well as NDT methods for evaluation of the final product.
- Brace manufacturer's participation in a recognized quality certification program.
- Certification should include documentation that the manufacturer's Quality Assurance Plan is in compliance with the requirements of the BRBF Provisions, the *Seismic Provisions for Structural Steel Buildings*, and the *Code of Standard Practice.* The manufacturing and quality control procedures should be equal to or better than those used to manufacture brace test specimens.

C16.2. Bracing Members

C16.2a. Composition

C16.2a.1. Steel Core

The steel core is composed of a yielding segment and steel core projections; it may also contain transition segments between the projections and yielding segment. The area of the yielding segment of the steel core is expected to be sized so that its yield strength is fairly close to the demand calculated from the applicable building code base shear. Designing braces close to the predicted required strengths will help ensure distribution of yielding over multiple stories in the building. Conversely, over-designing some braces more than others (for example, by using the same size brace on all floors), may result in an undesirable concentration of inelastic deformations in only a few stories. The length and area of the yielding segment, in conjunction with the lengths and areas of the non-yielding segments, determine the stiffness of the brace. The yielding segment length and brace inclination also determines the strain demand corresponding to the design story drift.

In typical brace designs, a projection of the steel core beyond its casing is necessary in order to accomplish a connection to the frame. Buckling of this unrestrained zone is an undesirable yield mode and must therefore be precluded.

In typical practice, the designer specifies the core plate dimensions as well as the steel material and grade. The steel stress-strain characteristics may vary significantly within the range permitted by the steel specification, potentially resulting in significant brace overstrength. This overstrength must be addressed in the design of connections as well as of frame beams and columns.

In order to reduce this source of overstrength, the designer may choose to specify a brace capacity corresponding to a defined displacement (typically 200 percent of the Design Story Drift) in the Design Documents. In addition, the designer may specify a limited range of acceptable yield stress in order to more strictly define the permissible range of core plate area. The brace supplier may then select the final core plate dimensions to meet the capacity requirement using the mill certificate or the results of a coupon test. The designer should be aware that this approach may result in a deviation from the calculated brace axial stiffness.The maximum magnitude of the deviation is dependent on the range of acceptable material yield stress. Designers following this approach should consider the possible range of stiffness in the building analysis in order to adequately address both the building period and expected drift.

C16.2a.2. Buckling-Restraining System

This term describes those elements providing brace stability against overall buckling. This includes the casing as well as elements connecting the core. The adequacy of the buckling-restraining system must be demonstrated by testing.

C16.2b. Testing

Testing of braces is considered necessary for this system. The applicability of tests to the designed brace is defined in Appendix T. Section C9.2a of the *Seismic Provisions*, which describes in general terms the applicability of tests to designs, applies to BRBF.

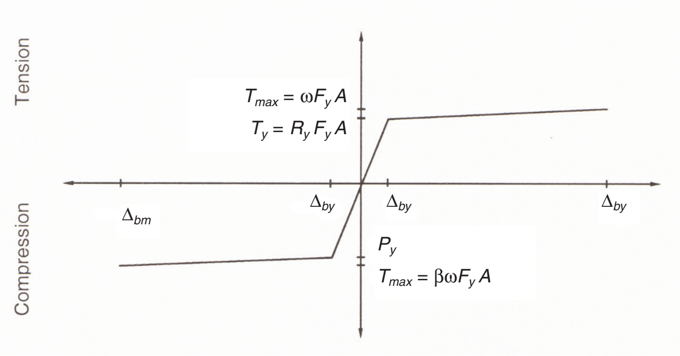


Fig. C-I-16.3. Diagram of Brace Force-Displacement.

BRBF designs require reference to successful tests of a similarly-sized test specimen and of a brace subassemblage that includes rotational demands. The former is a uniaxial test intended to demonstrate adequate brace hysteretic behavior. The latter is intended to verify the general brace design concept and demonstrate that the rotations associated with frame deformations do not cause failure of the steel core projection, binding of the steel core to the casing, or otherwise compromise the brace hysteretic behavior. A single test may qualify as both a subassemblage and a brace test subject to the requirements of T; for certain frame-type subassemblage tests, obtaining brace axial forces may prove difficult and separate brace tests may be necessary. A sample subassemblage test is shown in Figure C-T.1 (from Tremblay, 1999).

Tests cited serve another function in the design of BRBF: the maximum forces that the brace can deliver to the system are determined from test results. Calculation of these maximum forces is necessary for connection design and for the design of beams in V- and inverted-V configurations (see 16.4a.3). In order to permit a realistic design of these beams, two separate calculations are made. The compression-strength adjustment factor, β, accounts for the compression overstrength (with respect to tension strength) noted in buckling-restrained braces in recent testing (SIE, 1999). The tension strength adjustment factor, ω, accounts for material overstrength (R_y) and strain hardening. Figure C-I-16.3 shows a diagrammatic bilinear force-displacement relationship in which the compression strength adjustment factor β and the tension-strength adjustment factor ω are related to brace forces and nominal material yield strength. These quantities are defined as

$$\beta = \frac{\beta\omega F_y A}{\omega F_y A} = \frac{P_{\max}}{T_{\max}}$$

$$\omega = \frac{\omega F_y A}{F_y A} = \frac{T_{\max}}{F_y A}$$

where P_{max} is the maximum compression force and T_{max} is the maximum tension force within deformations corresponding to 200 percent of the design story drift (these deformations are defined as $2.0\Delta_{bm}$ in the Appendix on testing). The acceptance criteria for testing require that values of β and ω be greater than or equal to 1.0 for buckling-restrained braces.

C16.3. Bracing Connections

Bracing connections must not yield at force levels corresponding to the yielding of the steel core; they are therefore designed for the maximum force that can be expected from the brace. In the actual building frame, the use of slip-critical bolts designed at factored loads is encouraged (but not required) to greatly reduce the contribution of bolt slip to the total inelastic deformation in the brace. Because of the way bolt capacities are calibrated, the engineer should recognize that the bolts are going to slip at load demands 30 percent lower than published factored capacities. This slippage is not considered to be detrimental to behavior of the BRBF system and is consistent with the design approach found elsewhere in *Seismic Provisions* Section 7.2. See also commentary on Section C7.2. Bolt holes may be drilled or punched subject to the requirements of Section L2.5 of the *LRFD Specification for Structural Steel Buildings* (AISC, 1999).

Recent testing in Taiwan (Tsai, Weng, Lin, Chen, Lai, and Hsiao, 2003) has demonstrated that the stability of gusset-plate connections may be the most critical aspect of the design of BRBF. The tendency to instability may vary depending on the flexural stiffness of the connection portions of the buckling restrained brace and the degree of their flexural continuity with the casing. This aspect of BRBF design is the subject of continuing investigation and designers are encouraged to consult research publications as they become available. The stability of gussets may be demonstrated by testing, if the test specimen adequately resembles the conditions in the building. It is worth noting that during an earthquake the frame may be subjected to some out-of-plane displacement concurrent with the in-plane deformations, so a degree of conservatism in the design of gussets may be warranted.

C16.4. Special Requirements Related to Bracing Configuration

C16.4a. V-Type and Inverted-V-Type Bracing

In SCBF, V-bracing has been characterized by a change in deformation mode after one of the braces buckles (see *Seismic Provisions* Section C13.4a). This is due to the negative post-buckling stiffness, as well as the difference between tension and compression capacity, of traditional braces. Since buckling-restrained braces do not exhibit the negative secant stiffness associated with post-buckling deformation, and have only a small difference between tension and compression capacity, the practical requirements of the design provisions for this configuration are relatively minor. Figure C-I-16.4 shows the deformation mode that develops after one brace has yielded but before the yielding of the opposite brace completes the mechanism. This mode involves flexure of the beam and elastic axial deformation of the unyielded brace; it also involves inelastic deformation of the yielded brace that is much greater than the elastic deformation of the opposing brace. The drift range that corresponds to this deformation mode depends on the flexural stiffness of the beam. Therefore, where V-braced frames are used, it is required that a beam be provided that has sufficient stiffness, as well as strength, to permit the yielding of both braces within a reasonable story drift considering the difference in tension and compression capacities determined by testing.

The beam is expected to undergo this deflection, which is permanent, during moderate seismic events; a limit is therefore applied to this deflection. Additionally, the required brace deformation capacity must include the additional deformation due to beam deflection under this load. Since other requirements such as the brace testing protocol (T6.3) and the stability of connections (16.3c) depend on this deformation, engineers will find significant incentive to avoid flexible beams in this configuration. Where the special configurations shown in Figure C-I-13.3 of the *Seismic Provisions* are used, the requirements of this section are not relevant.

C16.5. Columns

Columns in BRBF are required to have compact sections because some inelastic rotation demands are possible. Columns are also required to be designed considering the maximum force that the adjoining braces are expected to develop.

C16.6. Beams

Like columns, beams in BRBF are required to have compact sections because some inelastic rotation demands are possible when beam-column connections are fully-restrained, as is expected to be the norm. Likewise, they are also required to be designed considering the maximum force that the adjoining braces are expected to develop.

Appendix T: Qualifying Cyclic Tests of Buckling Restrained Braces

CT1. Scope and Purpose

Development of the testing requirements in these provisions was motivated by the relatively small amount of test data on this system available to structural engineers. In addition, no data from the response of BRBFs to severe ground motion is available. Therefore, the seismic performance of these systems is relatively unknown compared to more conventional steel-framed structures.

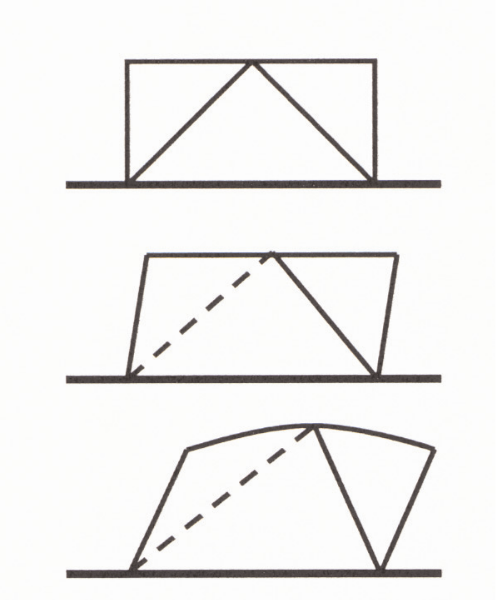


Fig. C-I-16.4. Post-yield, Pre-mechanism Change in Deformation Mode for V- and Inverted-V BRBF.

The behavior of a Buckling Restrained Brace Frame differs markedly from conventional braced frames and other structural steel seismic-force-resisting systems. Various factors affecting brace performance under earthquake loading are not well understood and the requirement for testing is intended to provide assurance that the braces will perform as required, and also to enhance the overall state of knowledge of these systems.

It is recognized that testing of brace specimens and subassemblages can be costly and time-consuming. Consequently, this Appendix has been written with the simplest testing requirements possible, while still providing reasonable assurance that prototype BRBFs based on brace specimens and subassemblages tested in accordance with these provisions will perform satisfactorily in an actual earthquake.

It is not intended that these provisions drive project-specific tests on a routine basis for building construction projects. In most cases, tests reported in the literature, or supplied by the brace manufacturer, can be used to demonstrate that a brace and subassemblage configuration satisfies the strength and inelastic rotation requirements of these provisions. Such tests, however, should satisfy the requirements of this Appendix.

The provisions have been written allowing submission of data on previously tested brace specimens and subassemblages, based on similar conditions. As the body of test data for each brace type grows, the need for additional testing is expected to diminish. The provisions allow for manufacturer-designed braces, through the use of the design methodology.

Most testing programs developed for primarily axial-load-carrying components focus largely on uniaxial testing. However, these provisions are intended to direct the primary focus of the program toward testing of a subassemblage that imposes combined axial and rotational deformations on the brace specimen. This reflects the view that the ability of the brace to accommodate the necessary rotational deformations cannot be reliably predicted by analytical means alone.

Subassemblage test requirements are discussed more completely in Section CT4.

Where conditions in the actual building differ significantly from the test conditions specified in this Appendix, additional testing beyond the requirements described herein may be needed to assure satisfactory brace performance. Prior to developing a test program, the appropriate regulatory agencies should be consulted to assure the test program meets all applicable requirements.

CT2. Symbols

The provisions require the introduction of several new variables. The quantity Δ_{bm} represents both an axial displacement and a rotational quantity. Both quantities are determined by examining the profile of the building at the design story drift, Δ_m, and extracting joint lateral and rotational deformation demands.

Determining the maximum rotation imposed on the braces used in the building may require significant effort. The engineer may prefer to select a reasonable value (in other words, interstory drift), which can be simply demonstrated to be conservative for each brace type, and is expected to be within the performance envelope of the braces selected for use on the project.

The brace deformation at first significant yield is used in developing the test sequence described in Section T6.3. The quantity is required to determine the actual cumulative inelastic deformation demands on the brace. If the nominal yield stress of the steel core were used to determine the test sequence, and significant material over-strength were to exist, the total inelastic deformation demand imposed during the test sequence would be overestimated.

CT3. Definitions

Two types of testing are referred to in this Appendix. The first type is subassemblage testing, described in T4, an example of which is illustrated in Figure CT.1.

The second type of testing described in T5 as brace test specimen testing is permitted to be uniaxial testing.

CT4. Subassemblage Test Specimen

The objective of subassemblage testing is to verify the ability of the brace, and in particular its steel core extension and buckling restraining mechanism, to accommodate the combined axial and rotational deformation demands without failure.

It is recognized that subassemblage testing is more difficult and expensive than uniaxial testing of brace specimens. However, the complexity of the brace behavior due to the combined rotational and axial demands, and the relative lack of test data on the performance of these systems, indicates that subassemblage testing should be performed.

Subassemblage testing is not intended to be required for each project. Rather, it is expected that brace manufacturers will perform the tests for a reasonable range of axial loads, steel core configurations, and other parameters as required by the provisions. It is expected that this data will subsequently be available to engineers on other projects. Manufacturers are therefore encouraged to conduct tests that establish the device performance limits to minimize the need for subassemblage testing on projects.

Similarity requirements are given in terms of measured axial yield strength of both the prototype and the test specimen braces. This is better suited to manufacturer's product testing than to project-specific testing. Comparison of mill certificate or coupon test results is a way

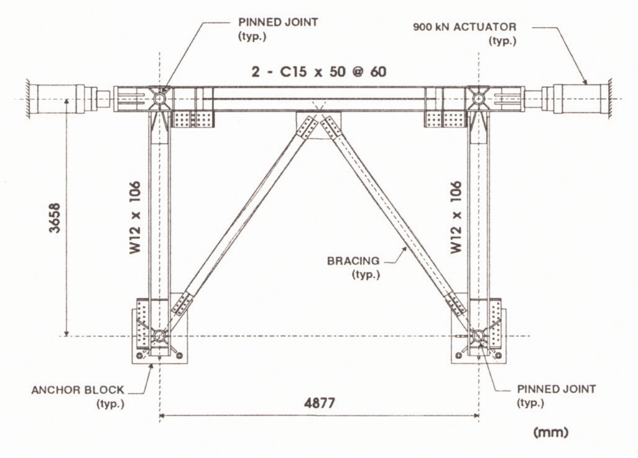


Fig. CT.1. Example of test subassemblage.

to establish a similarity between the subassemblage test specimen brace and the prototype braces. Once similarity is established, it is acceptable to fabricate test specimens and prototype braces from different heats of steel.

A variety of subassemblage configurations are possible for imposing combined axial and rotational deformation demands on a test specimen. Some potential subassemblages are shown in Figure CT.2. The subassemblage need not include connecting beams and columns provided that the test apparatus duplicates, to a reasonable degree, the combined axial and rotational deformations expected at each end of the brace.

Rotational demands may be concentrated in the steel core extension in the region just outside the buckling restraining mechanism. Depending on the magnitude of the rotational demands, limited flexural yielding of the steel core extension may occur. Rotational demands can also be accommodated by other means, such as tolerance in the buckling restraint layer or mechanism, elastic flexibility of the brace and steel core extension, or through the use of pins or spherical bearing assemblies. It is in the engineer's best interest to include in a subassemblage testing all components that contribute significantly to accommodating rotational demands. The use of pins, while accommodating rotational demands, creates the potential for instability; and should be carefully considered by the engineer.

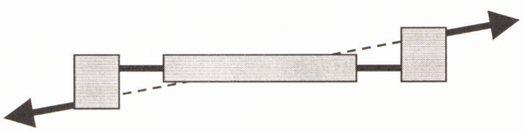
It is intended that the subassemblage test specimen be larger in axial-force capacity than the prototype. However, the possibility exists for braces to be designed with very large axial forces. Should the brace yield force be so large as to make subassemblage testing impractical, the engineer is expected to make use of the provisions that allow for alternate testing programs, based on building official approval and qualified peer review. Such programs may include, but are not limited to, non-linear finite element analysis, partial specimen testing, and reduced-scale testing, in combination with full-scale uniaxial testing where applicable or required.

The steel core material was not included in the list of requirements. The more critical parameter, calculated margin of safety for the steel core projection stability, is required to meet or exceed the value used in the prototype. The method of calculating the steel core projection stability should be included in the design methodology.

CT5. Brace Test Specimen

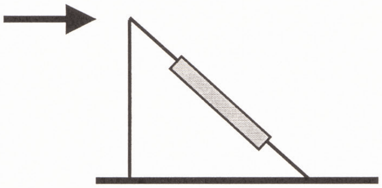
The objective of brace test specimen testing is to establish basic design parameters for the BRBF system.

It is recognized that the fabrication tolerances used by brace manufacturers to achieve the

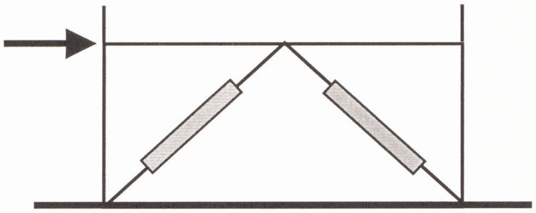


Eccentric Loading of Brace

Loading of Brace with Constant Imposed Rotation



Loading of Brace and Column



Loading of Braced Frame

Fig. CT.2. Schematic of possible test subassemblages.

required brace performance may be tighter than those used for other fabricated structural steel members. The engineer is cautioned against including excessively prescriptive brace specifications, as the intent of these provisions is that the fabrication and supply of the braces is achieved through a performance-based specification process. It is considered sufficient that the manufacture of the test specimen and the prototype braces be conducted using the same quality control and assurance procedures, and the braces be designed using the same design methodology.

The engineer should also recognize that manufacturer process improvements over time may result in some manufacturing and quality control and assurance procedures changing between the time of manufacture of the brace test specimen and of the prototype. In such cases reasonable judgment is required.

If the steel core or steel core projection is not biaxially symmetric, the engineer should ensure that the same orientation is maintained in both the test specimen and the prototype.

The allowance of previous test data (similarity) to satisfy these provisions is less restrictive for uniaxial testing than for subassemblage testing. Subassemblage test specimen requirements are described in Section CT4.

A considerable number of uniaxial tests have been performed on some brace systems and the engineer is encouraged, wherever possible, to submit previous test data to meet these provisions. Relatively few Subassemblage tests have been performed. This type of testing is considered a more demanding test of the overall brace performance.

CT5.4 Connection Details

In many cases it will not be practical or reasonable to test the exact brace connections present in the prototype. These provisions are not intended to require such testing. In general, the demands on the steel core extension to gusset-plate connection are well defined due to the known axial capacity of the brace and the limited flexural capacity of the steel core extension. The subsequent design of the bolted or welded connection is relatively well-understood and it is not intended that these connections become the focus of the testing program.

For the purposes of utilizing previous test data to meet the requirements of this Appendix, the requirements for similarity between the brace and subassemblage brace test specimen can be considered to exclude the steel core extension connection to frame.

CT5.5 Materials

The intent of the provisions is to allow test data from previous test programs to be presented where possible. See CT4 for additional commentary.

CT5.6. Connections

The intent of this provision is to ensure that the end connections of the brace test specimen reasonably represent those of the prototype. It is possible that due to fabrication or assembly constraints variations in fit-up, faying-surface preparation, or bolt or pin hole fabrication and size may occur. In certain cases, such variations may not be detrimental to the qualification of a successful cyclic test. The final acceptability of variations in brace-end connections rests on the opinion of the building official.

CT6.3. Loading Sequence

The subassemblage test specimen is required to undergo combined axial and rotational deformations similar to those in the prototype. It is recognized that identical braces, in different locations in the building, will undergo different maximum axial and rotational deformation demands. In addition, the maximum rotational and axial deformation demands may be different at each end of the brace. The engineer is expected to make simplifying assumptions to determine the most appropriate combination of rotational and axial deformation demands for the testing program.

Some subassemblage configurations will require that one deformation quantity be fixed while the other is varied as described in the test sequence above. In such a case, the rotational quantity may be applied and maintained at the maximum value, and the axial deformation applied according to the test sequence. The engineer may wish to perform subsequent

Table C-T.1. Example Brace Testing Protocol

Cycle Deformation	Inelastic Deformation	Cumulative Inelastic Deformation
$2\ @\ \Delta_{by}$	$= 2*4*(\Delta_{by} - \Delta_{by}) = 0\Delta_{by}$	$0\Delta_{by} \quad = 0\Delta_{by}$
$2\ @\ 0.5\Delta_{bm} = 4\ @\ 2.0\Delta_{by}$	$= 2*4*(2.0\Delta_{by} - \Delta_{by}) = 8\Delta_{by}$	$0\Delta_{by} + 8\Delta_{by} = 8\Delta_{by}$
$2\ @\ \Delta_{bm} = 4\ @\ 4.0\Delta_{by}$	$= 2*4*(4.0\Delta_{by} - \Delta_{by}) = 24\Delta_{by}$	$8\Delta_{by} + 24\Delta_{by} = 32\Delta_{by}$
$2\ @\ 1.5\Delta_{bm} = 2\ @\ 6.0\Delta_{by}$	$= 2*4*(6.0\Delta_{by} - \Delta_{by}) = 40\Delta_{by}$	$32\Delta_{by} + 40\Delta_{by} = 72\Delta_{by}$
$2\ @\ 2.0\Delta_{bm} = 2\ @\ 8.0\Delta_{by}$	$= 2*4*(8.0\Delta_{by} - \Delta_{by}) = 56\Delta_{by}$	$104\Delta_{by} + 56\Delta_{by} = 160\Delta_{by}$
$2\ @\ 1.5\Delta_{bm} = 2\ @6.0\Delta_{by}$	$= 2*4*(6.0\Delta_{by} - \Delta_{by}) = 40\Delta_{by}$	$160\Delta_{by} + 40\Delta_{by} = 200\Delta_{by}$

Cumulative inelastic deformation at end of protocol = 200 Δ_{by}.

tests on the same subassemblage specimen to bound the brace performance.

The loading sequence requires each tested brace to achieve ductilities corresponding to 2.0 times the design story drift and a cumulative inelastic axial ductility capacity of 140. Both of these requirements are based on a study in which a series nonlinear dynamic analyses was conducted on model buildings in order to investigate the performance of this system; the ductility capacity requirement represents a mean of response values and the cumulative ductility capacity requirement is a mean plus standard deviation value (Sabelli, 2003). In that study, buildings were designed and models of brace hysteresis selected so as to maximize the demands on braces. It is therefore believed that these requirements are more severe than the demands that typical braces in typical designs would face under their design-basis ground motion, perhaps substantially so. It is also expected that as more test data and building analysis results become available these requirements may be revisited.

The ratio of brace yield deformation (Δ_{by}) to the brace deformation corresponding to the design story drift (Δ_{bm}) must be calculated in order to define the testing protocol. This ratio is typically the same as the ratio of the displacement amplification factor (as defined in the applicable building code) to the actual overstrength of the brace; the minimum overstrength is defined in section 16.2a.1.a. Engineers should note that there is a minimum brace deformation demand corresponding to 1 percent story drift (T2); provision of overstrength beyond that required to so limit the design story drift may not be used as a basis to reduce the testing protocol requirements.

Table C-T.1 shows an example brace test protocol. For this example, it is assumed that the brace deformation corresponding to the design story drift is four times the yield deformation; it is also assumed that the design story drift is larger than the 1 percent minimum. The test protocol is then constructed from steps 1 through 4 of T6.3. In order to calculate the cumulative inelastic deformation, the cycles are converted from multiples of brace deformation at the design story drift (Δ_{bm}) to multiples of brace yield deformation (Δ_{by}). Since the cumulative inelastic drift at the end of the $2.0\Delta_{bm}$ cycles is less than the minimum of $200\Delta_{by}$ required for brace tests, additional cycles to Δ_{bm} are required. At the end of three such cycles, the required cumulative inelastic deformation has been reached.

Dynamically applied loads are not required by these provisions. The use of slowly applied cyclic loads, widely described in the literature for brace specimen tests, is acceptable for the purposes of these provisions. It is recognized that dynamic loading can considerably increase the cost of testing, and that few laboratory facilities have the capability to apply dynamic loads to very large-scale test specimens. Furthermore, the available research on dynamic loading effects on steel test specimens has not demonstrated a compelling need for such testing.

If rate-of-loading effects are thought to be potentially significant for the steel core material used in the prototype, it may be possible to estimate the expected change in behavior by performing coupon tests at low (test cyclic loads) and high (dynamic earthquake) load rates. The results from brace tests would then be factored accordingly.

CT8. Materials Testing Requirements

Tension testing of the steel core material used in the manufacture of the test specimens is required. In general, there has been good agreement between coupon test results and observed tensile yield strengths in full-scale uniaxial tests. Material testing required by this appendix is consistent with that required for testing of beam-to-column moment connections. For further information on this topic refer to Section CS8 of the *Seismic Provisions.*

CT10. Acceptance Criteria

The acceptance criteria are written so that the minimum testing data that must be submitted is at least one subassemblage test and at least one uniaxial test. In most cases the subassemblage test also qualifies as a uniaxial test provided the requirements of section T5 are met. If project specific subassemblage testing is to be performed it may be simplest to perform two subassemblage tests to meet the requirements of this section. For the purposes of these requirements a single subassemblage test incorporating two braces in a chevron or other configuration is also considered acceptable.

Depending on the means used to connect the test specimen to the subassemblage or test apparatus, and the instrumentation system used, bolt slip may appear in the load versus displacement history for some tests. This may appear as a series of spikes in the load versus displacement plot and is not generally a cause for concern, provided the behavior does not adversely affect the performance of the brace or brace connection.

These acceptance criteria are intended to be minimum requirements. The 1.3 limit in Section T10.5 is essentially a limitation on β. These provisions were developed assuming that $\beta < 1.3$ so this provision has been included in the test requirements. Most currently available braces should be able to satisfy this requirement.

REFERENCES

American Institute of Steel Construction (AISC) (2002), *Seismic Provisions for Structural Steel Buildings*, AISC, May 21, Chicago.

AISC (2000), *Code of Standard Practice for Steel Buildings*, AISC, March 7, Chicago.

AISC (1999), *Specification for Structural Steel Buildings*, AISC, December 27, Chicago.

American Society of Civil Engineers (ASCE) (2002), *Minimum Design Loads for Buildings and Other Structures*, SEI/ASCE 7-02, Reston, VA.

Clark, P., Aiken, I., Kasai, K., Ko, E., and Kimura, I. (1999), "Design Procedures for Buildings Incorporating Hysteretic Damping Devices," *Proceedings 68th Annual Convention*, pp. 355-371, Structural Engineers Association of California, Sacramento, CA.

Federal Emergency Management Agency (FEMA) (2000), *NEHRP Recommended Provisions for Seismic Regulations for New Buildings*, FEMA, Washington, D.C.

FEMA (2003), *NEHRP Recommended Provisions for New Buildings and Other Structures*, FEMA 450, Washington, D.C.

International Conference of Building Officials (ICBO) (1997), *Uniform Building Code*, Whittier, CA.

Kalyanaraman, V., Sridhara, B.N., and Mahadevan, K. (1994), "Sleeved Column System," *Proceedings of the SSRC Task Group Meetings and Task Force Sessions*, Lehigh University, Bethlehem, PA.

Kalyanaraman, V., Sridhara, B.N., and Thairani, V. (1998), "Core Loaded Earthquake Resistant Bracing Design," *Proceedings of the 2nd International Conference on Steel Construction*, San Sebastian, Spain.

Kalyanaraman, V., Sridhara, B.N., Mahadevan, K., Thairani, V., and Ramachandrran, B. (1998), "A Sleeved Bracing System for Earthquake Resistant Design of Tall Buildings," Symposium on Earthquake Engineering, Univ. of Roorkee, December 17-19.

Kasai, K., Fu, Y., and Watanabe, A. (1998), "Passive Control Systems for Seismic Damage Mitigation," *Journal of*

Structural Engineering, Vol. 124, No. 5, pp. 501-512, (May), American Society of Civil Engineers, Reston, VA.

Lopez, W., Gwie, D.S., Lauck, T.W., and Saunders, C.M. (2004), "UC Berkeley Stanley Hall—Structural Design and Experimental Verification of a Buckling-Restrained Braced Frame System," *Engineering Journal*, Vol. 41, No. 4, 4th Quarter, AISC.

Prasad, B. (1992), "Experimental Investigation of Sleeved Column," *Proceedings of the 33rd Structural Dynamics and Materials Conference*, American Institute of Aeronautics and Astronautics, Dallas.

Reina, P., and Normile, D. (1997), "Fully Braced for Seismic Survival," *Engineering News-Record*, pp. 34-36, July 21, The McGraw Hill Companies, New York.

Sabelli, R., Mahin, S., and Chang, C. (2003), "Seismic Demands on Steel Braced Frame Buildings with Buckling-Restrained Braces," *Engineering Structures,* 25 (2003), pp. 655-666.

Seismic Isolation Engineering for Nippon Steel Corporation (1999), "Tests of Nippon Steel Corporation Unbonded Braces," Report to Ove Arup & Partners, CA.

Seismic Isolation Engineering (SIE) (1999), "Report on Pre-Prototype Tests of Yielding Braces," CA.

Sridhara, B.N. (1990), "Sleeved Column-As a Basic Compression Member," *4th International Conference of Steel Structures and Space Frames*, Singapore.

Tsai, K.-C., Weng, Y.-T., Lin, M.-L., Chen, C.-H., Lai, J.-W., and Hsiao, P.-C. (2003), "Pseudo Dynamic Tests of a Full-Scale CFT/BRB Composite Frame: Displacement Based Seismic Design and Response Evaluations," *Proceedings of the International Workshop on Steel and Concrete Composite Construction* (IWSCCC-2003), Report No. NCREE-03-026, pp. 165-176, National Center for Research in Earthquake Engineering, October 8-9, 2003, Taipei, Taiwan.

Tremblay, R., Degrange, G., and Blouin, J. (1999), "Seismic Rehabilitation of a Four-Storey Building with a Stiffened Bracing System," *Proceedings of 8th Canadian Conference on Earthquake Engineering*, pp. 549-554, Canadian Association for Earthquake Engineering, Vancouver, B.C.

Wada, A., Connor, J., Kawai, H., Iwata, M., and Watanabe, A. (1994), "Damage Tolerant Structure," *ATC-15-4 Proceedings of 5th US-Japan Workshop on the Improvement of Building Structural Design and Construction Practices*, pp. 27-39, Applied Technology Council, Redwood City, CA.

Wada, A., Saeki, E., Takeuchi, T., and Watanabe, A. (1998), "Development of Unbonded Brace," Nippon Steel's Unbonded Braces (promotional document), pp. 1-16, Nippon Steel Corporation Building Construction and Urban Development Division, Tokyo, Japan.

Watanabe, A., Hitomi, Y., Saeki, E., Wada, A., and Fujimoto, M. (1988), "Properties of Brace Encased in Buckling-Restraining Concrete and Steel Tube," *Proceedings of 9th World Conference on Earthquake Engineering,* Vol. IV, pp. 719-724, Japan Association for Earthquake Disaster Prevention, Tokyo-Kyoto, Japan.