Design for Improved Performance of Buckling-Restrained Braced Frames

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Abstract

The buckling-restrained braced frame (BRBF) represents a significant improvement in seismic bracing techniques available to structural engineers, and its application in areas of high seismic risk is growing rapidly. The predictable axial yielding mechanism of the cost-competitive BRBF, together with its "tuneable" resistance, makes it more versatile, and presumably more reliable, than traditional brace types. In current practice, the beam-column connection at the BRBF gusset is normally a rigid, field-welded assembly, which creates a stiff moment-resisting connection. However, it has been demonstrated that the introduction of drift-related joint rotation with integrally welded beams, columns and gusset plates in a BRBF can have the following potentially serious negative effect on components of BRBF's:

- "Pinching" of the gusset plate,
- Possible yielding of column webs or flanges,
- Distress to field-welded beam-column connections,
- An unintentionally high fraction of structure base shear may be resisted through moment frame action, rather than by the highly reliable buckling-restrained braces themselves.

An alternate BRBF connection design is described that significantly reduces the undesirable effects of beam/column/gusset interaction, and which can therefore improve the potential of the BRBF as a performance-based seismic design solution. The alternate approach may be implemented with or without the use of a moment-resisting frame.

Introduction

The buckling-restrained brace (BRB) is a relatively new addition to the SE's tool kit for performance-based seismic engineering. Its positive performance features include an axial yielding mechanism that is predictable, stable, repeatable, and relatively economical. The stiffness, strength, and deformation capacity may be "customized" to meet the needs of a specific project. It is not prone to brittle fracture, or to the other undesirable behavioral modes of concentrically braced frames.[8] The BRB consequently offers the structural engineer a more versatile and reliable lateral brace than existed previously.

BRB's and Buckling-restrained brace frames (BRBF) have recently been described, studied, and tested by numerous researchers.[1,2,4,9]

Presently, BRB's are available from several manufacturers, and are made with two basic end connection types: bolted and pinned. BRB's may be employed in single diagonal, V, or chevron framing configurations.

Current model codes do not address BRBF's; however, the 2003 edition of NEHRP provisions[5] includes provisions for the design and testing of BRBF's that will presumably be adopted by future editions of model building codes, and by the 2005 AISC seismic provisions.

Engineering Advantages of the BRB

From the perspective of the practicing structural engineer, BRB's possess many of the most useful features of both braces and dampers:

- Dependability of resistance – consistent force-displacement loops (Fig. 1),
- Energy dissipation capacity,

- Adjustable resistance,
- Simple mode of behavior of the brace element – direct axial deformation – provides similar resistance in both compression and tension,
- Precludes the need for "opposing" brace inclination along a given bracing line, simplifying the bracing layout possibilities relative to architectural requirements.

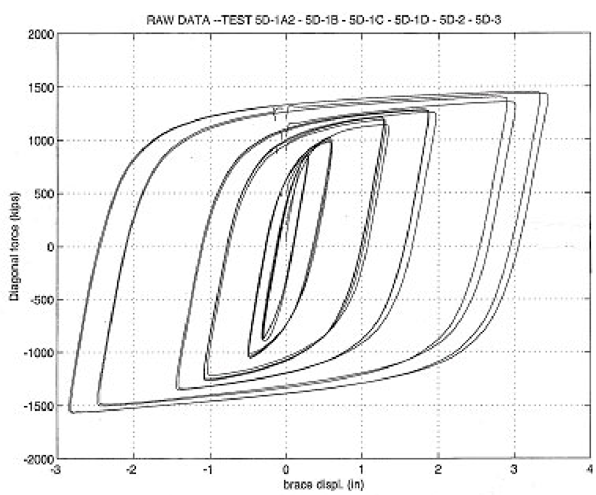

Figure 1

BRB tests in the U.S. and Japan have demonstrated the robust and consistent cyclic post-yield resistance and energy dissipation of the BRB, together with high strain capacity. Structural engineers aware of these tests recognized the possible use of the BRBF as a high-performance bracing element that had the potential to outperform earlier bracing systems, and to be replaceable if damaged.

Seismic Drift Response of BRBF's

Most engineers regard diagonally braced systems as being substantially stiffer than similarly proportioned moment frame systems. In fact, the anticipated interstory drift response of a BRBF system, if designed in accordance with the NEHRP provisions, is significantly higher than might be expected for an ideally performing CBF. BRBF drift can aproach that for a SMRF system of similar proportions. Refer to Table 1 for a summary of approximate ranges of expected peak interstory drift values for various lateral systems, based on an informal survey by the authors of recently designed projects in California.

Standard Frame Connection Detailing for BRBF's

Like other brace types, BRB's require a significant gusset to transfer seismic forces from the brace to the beams and columns.

BRBF gusset connection forces, in accordance with the NEHRP provisions, are calculated using amplification factors for higher-than-expected yield stress, cyclic strain hardening, and slightly elevated resistance in compression.

Table 1
Range of Typical Maximum Inelastic Interstory Drifts for Various Lateral Systems

Lateral System	**Range of Expected Drift**
SMRF	1.5% - 2.5%
BRBF	0.5% - 2.0%
SCBF	0.5% - 1% (potentially much higher considering inelastic buckling)
EBF	0.5% - 1.5%

These forces frequently dictate large interface dimensions between the gusset, beam, and column. Rigidity of the beam/column/gusset connection is therefore practically unavoidable. Examples of "standard" BRBF connections are shown in Figures 2, 3, and 4.

Figure 2

The presence of a large brace gusset creates a joint zone even larger and more complicated than that of a moment frame connection. The high corresponding rigidity of such a joint poses behavioral challenges to the BRBF, relative to the anticipated interstory drifts discussed above.

Figure 3

Figure 4

Potential Negative Effects of Standard BRBF Detailing Techniques

The default presence of a highly rigid moment connection in the BRBF leads to high flexural participation of the beams and columns in the overall lateral load resistance. This participation of the moment frame portion of the BRBF in lateral resistance was demonstrated during the UCB tests. [4] Refer to Figure 5 for a photograph of the gusset of the UCB specimen. The results of those tests indicated that the moment frame portion of the BRBF with standard rigid connections ultimately resisted between 40 and 60 percent of the total applied lateral load. The drift experienced by the BRBF caused the following behavior in the surrounding frame:

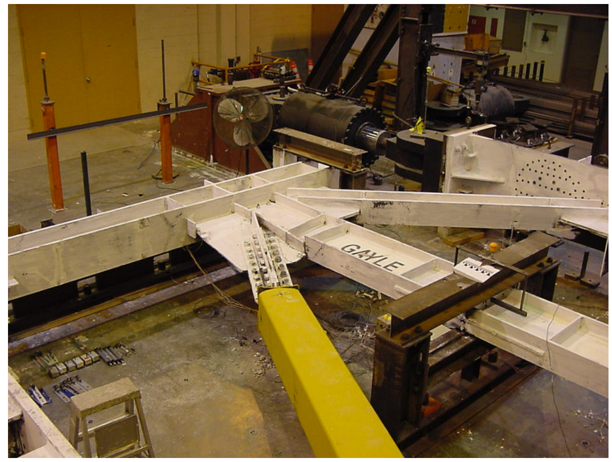

Figure 5

- Gusset "pinching" and consequent buckling,
- High percentage of lateral load resisted not by BRB, but by the surrounding moment frame,
- Shortening of the free length of the column due to the presence of a large gusset, and resulting large moments and shears in the column,
- Shear yielding in column web,
- Beam flange fracture at the beam-column connection, reminiscent of Northridge-type brittle fracture.

In summary, the brace performed extremely well, but the surrounding moment frame was the de facto "primary" lateral force-resisting element, rather than the BRB. Although the entire subassemblage performed past the design drift expectations, the ultimate failure mode was brittle fracture of the beam flange at the termination of the gusset plate. Prior to failure, the beam-column joint, gusset, and the column itself experienced significant yielding, and the gusset buckled due to pinching.

One could conclude that the performance of the UCB test specimen standard detailing is acceptable with respect to life safety goals of building codes; however, the damage suffered by the connections, columns, and beams would be difficult if not practically impossible to repair. This finding implies that the standard detailing approach for BRBF's is not conducive to seismic performance standards higher than life safety.

Hospital designers[6] resolved this shortcoming by increasing the strength and corresponding post-elastic stiffness of the BRBF to decrease expected drift, thus reducing the risk of undesirable connection behavior. In effect, this approach reduces the "R" value for the BRBF to a value significantly lower than allowed by the NEHRP recommended provisions, and consequently dictates increased strengths for all components of the BRBF, including beams and columns. The detailed nonlinear analytical study of the BRBF assembly discussed in Reference 6 concluded that the behavior of the gusset and beam-column connection zones is problematic.

Alternative Detailing Approach for Improved BRBF Behavior

The undesirable behavior associated with standard BRBF connection detailing motivated Forell/Elsesser Engineers to explore alternate connection configurations for BRBF's. This effort was guided by the following specific behavioral and economic objectives for BRBF connections:

- Reduction of vulnerability of the beam/column/ gusset connection to drift-induced damage,
- Reduction of moment frame action to ease the flexural demand on BRBF beams and columns, thus reducing the possibility of beam and column distress as well as member size and cost,
- Reduction of time-consuming and expensive field welding of beam and gusset connections,
- Where a supplemental moment frame is desired, make it secondary rather than primary.

The key to achieving the above objectives is to introduce a moment release or hinge between the beam and column while maintaining sufficient stiffness in the beam-column connection for compatibility with the rigid gusset. Placement of the hinge directly at the face of the column is not practical, however, due to the location and load transfer demands of the gusset. Therefore, the connection developed to satisfy the listed objectives utilizes a hinge in the in the beam beyond the gusset plate. Refer to Figure 6, which illustrates the concept for the case of a pinned-end type brace. The alternate detail shown may also be used with a bolted brace. An isometric view of the alternate connection at the base of a brace, for the case of a pinned end brace, is shown in Figure 7.

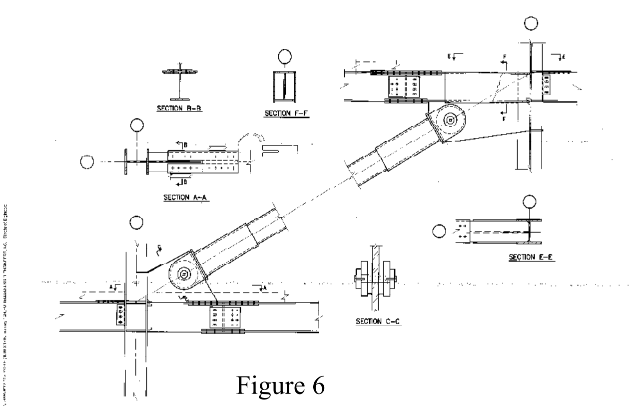

Figure 6

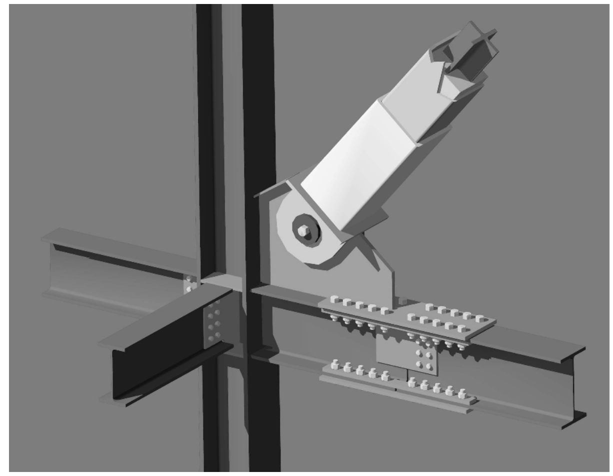

Figure 7

The connection shown is for a single-diagonal brace configuration. With proper design, the solution could also be adapted to a chevron or V configuration.

The hinge is located at the top flange of the beam. A similar bolted plate connection is provided at the bottom flange, however the bolt holes on one side of the splice are slotted to allow free slippage at the bottom flange splice. A similar slotted bolt hole configuration is used at the web shear plate connection.

The gusset and beam stub are shop welded to the column. This column may thus be delivered to the site as a "tree" with no welding required at the site.

Anticipated Behavior of Alternate BRBF Hinge Connection

The hinge is comprised of field-bolted cover plates, or flex plates. The connection is detailed to allow rotation to occur about the top flange, with no rotational resistance generated by the beam web or bottom flange. By placing the center of rotation at the top flange, (as close to the deck as possible), the formation of a large couple (and the resulting beam and column bending moments) between the deck and beam is avoided. The bending moment in the BRBF elements resulting from frame drift is therefore limited to a small moment generated from the bending of the flex plates, together with a small T-C couple generated between the flex plates and the deck.

The frame deformation pattern associated with the alternate detail is illustrated in Figure 8.

Bending of the flex plates is facilitated by a slight tapering of the upper and lower surfaces of the top flange to preclude a concentration of curvature of the flex plates. Refer to Figure 9 for an illustration of the tapered flange.

This tapering permits the plastic hinge length of the flex plates to be the clear distance between the first row of bolts on either side of the splice centerline.

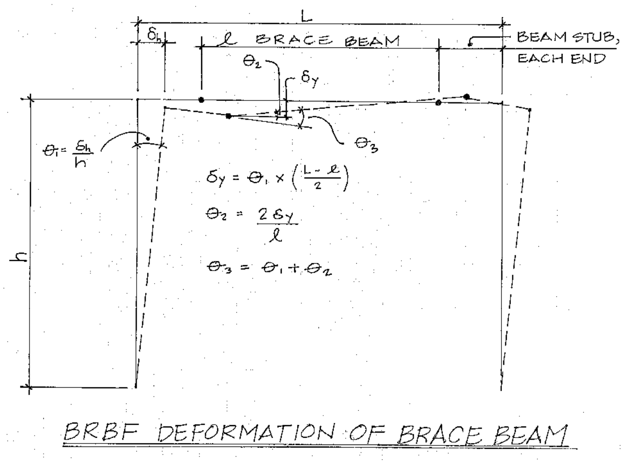

Figure 8

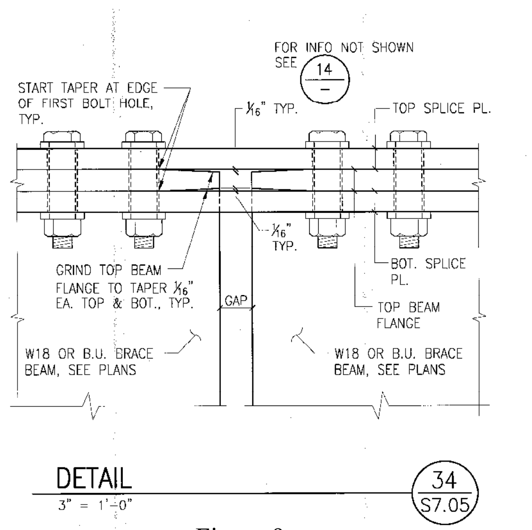

Figure 9

The slotted connection at the bottom flange does not transfer tension. The sole function of the bottom flange connection is to stabilize the brace beam flange out of plane.

The flex plates at the top flange also transfer all horizontal drag forces from brace to beam. The top flange location is ideal for this function, since the deck reactive mass generates most of the horizontal inertial forces, and since the deck is actually the primary path for tributary drag forces at each floor level.

The beam-column collector connection immediately outside the BRBF incorporates a simple shop-welded, field-bolted flange plate at the top flange of the beam to transmit drag forces, and a slotted bolted shear plate to allow rotation, similar to the hinged connection discussed above.

Behavior of Columns, Beams, and Gussets with Alternate BRBF Connection

The beam hinge connection allows the beam to freely rotate relative to the column as the frame undergoes drift displacement, thus flexurally uncoupling the beam and column at the end of the gusset. The hinge consequently prevents the frame from resisting moments due to interstory drift. Thus, the beams and columns support gravity loading and seismically-induced axial loads only. Drift-induced column and beam moments are therefore minimized, and gusset "pinching" is prevented.

Special Design Considerations for Alternate BRBF Connection

The brace work point is situated at the top flange level rather than at the usual beam centerline level to provide a consistent (non-eccentric) load path between the brace, deck, flex plates, and beam. The design of the gusset must consider this unusual alignment with respect to the moments imparted from the gusset to the beam and column. Proper consideration of the work point alignment may be accomplished using the uniform force method for the gusset plate design calculations.

The lateral analysis model should consider the top flange location of the brace work point.

The brace beam design must consider the eccentricity of the drag force applied through the top flange, in combination with gravity load effects. This consideration may result in a heavier beam section than if the beam and brace were concentric. However, this effect is offset by a reduction of frame moments due to the presence of the hinge, as discussed above.

The flex plates may be conservatively designed using the force $\beta\omega P_{ysc}$, as required for bracing connections in the 2003 NEHRP Recommended Provisions.[5] However, consideration must also be given to cyclic flexural yielding of the flex plates. One approach is to check combined axial strain in the flex plates due to tension (or compression) and flexure, and to compare the total strain with expected ultimate strain for the flex plate material. The flexural post-yield strain in the flex plates should normally be relatively low, given that the flexural height of the plates is merely their thickness. This implies that the flex plates should be kept as thin as practically possible, while still providing sufficient thickness to prevent buckling of the flex plates due to compressive drag forces.

The flex plate should be detailed to resist the minimum possible amount of bending moment due to drift-induced rotation. Consequently, the holes for the bolts connecting the flex plates to the top flange of the beam should be checked to verify that they provide sufficient clearance from the bolt shank to allow a slight relative slippage between the flange and the flex plates, in order that the sandwiched plates do not behave "compositely." Refer to the sample calculation shown in Figure 10. It may be beneficial to prohibit fully tensioning the flex plate bolts, to minimize clamping effects and further inhibit composite action of the sandwiched plates.

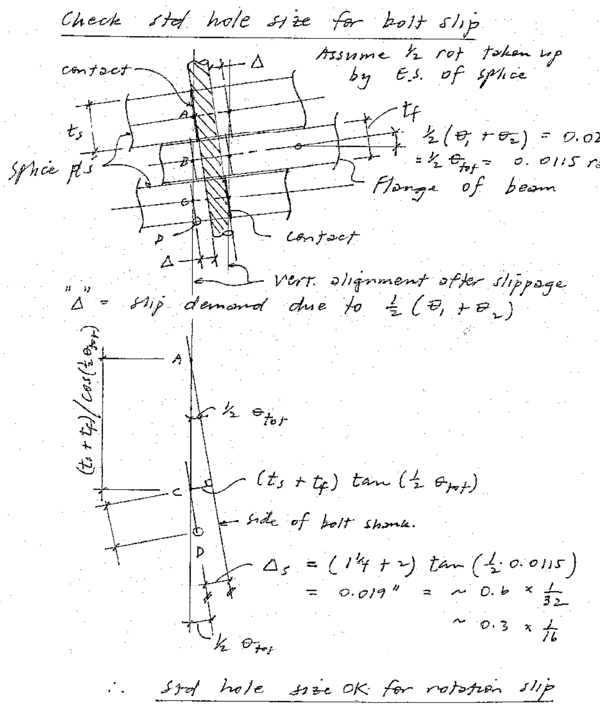

Figure 10

Since, for the alternate connection, the columns of the BRBF are not flexurally restrained by the beams, the rotations at the brace ends are somewhat higher than for a standard BRBF connection. The brace end rotation should be evaluated and addressed in the brace procurement specifications to ensure that the brace end rotation capacity is sufficient. Alternatively, pin-ended braces may be used.

Fig 6 illustrates that the alternate connection at the upper end of the brace is offset from the column more than for the standard connection type, due to the raised work point location. The bottom flange of the beam must therefore be stabilized out-of-plane where the brace line intersects the bottom flange. This may be achieved using a bracing beam, or by boxing the beam locally to enhance torsional stiffness and out-of-plane strength of the beam.

Use of Moment Frames with BRBF's

The standard BRBF connection automatically integrates the brace into a moment frame, thus forcing the two distinctly different systems to respond together. In contrast, the alternate BRBF connection intentionally eliminates the integration of BRB and moment frame for the reasons discussed above. Some BRBF applications may benefit from the redundancy of a moment frame, such as for a dual system. For example, a moment frame might be expected to remain elastic past the point where the BRB yields, providing for a beneficial yielding sequence that could help limit residual drifts and provide some restoring force. In this case, the alternate BRBF connection allows for a moment frame to be effectively incorporated in parallel with, but separately from, the BRBF by placing it outside the BRBF bay. This approach precludes the negative behavioral aspects of the interaction of the two different systems.

Conclusion

An alternate type of framing connection has been developed to improve the reliability, utility, and performance of buckling restrained braced frames. This approach allows for the occurrence of joint rotation while minimizing undue stress in columns, gussets, and beam-column joints. This alternate connection type is field-bolted and thus minimizes the need for field welding. The alternate connection type can be used in parallel with a separate moment frame system if desired, thus eliminating the negative aspects of the current approach of integrating buckling restrained braces directly into a moment frame.

By flexurally decoupling the beam from the column, it should be possible to minimize damage to the primary superstructure elements that would be difficult and expensive to repair, and to derive the post-elastic structural deformation from the BRB alone, which could be replaced if necessary. Use of such hinging connections can thus enhance the reliability of buckling restrained braced frames as a performance-based seismic design tool.

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