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CONNECTION PERFORMANCE OF BUCKLING RESTRAINED BRACED FRAMES

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SUMMARY

This paper discusses research that was carried out for the first hospital project in California to use the Buckling Restrained Brace Frame (BRBF) as its seismic lateral system, which was subject to the Office of Statewide Health and Planning (OSHPD) approval.

Arup introduced the Buckling Restrained Brace (BRB) to California in 1999, having successfully employed it on a number of Japanese projects. Arup has since been involved with rigorous research, testing and verification of the new system to meet Californian requirements.

Arup has used LS-DYNA to perform virtual tests on finite-element models to refine the design and to set performance criteria. Members and connections were modeled explicitly, so that local behavior could be assessed. This approach was validated against a set of full-scale tests that were carried out on a BRBF at UC Berkeley (using Nippon Steel's Unbonded Braces™). Arup constructed a full model using shell elements and analyzed it using test input drifts, which demonstrated good agreement with the test results.

Further virtual tests have also shown that BRBs perform excellently but that current braced frame connection detailing results in considerable yielding and stress concentrations, which in turn limit on the performance of the frame. Arup has been investigating alternative connection configurations to improve the frame performance, and our findings are presented in this paper.

INTRODUCTION

The Unbonded Brace™

An Unbonded Brace™ is a buckling-restrained brace where Euler buckling of the central steel core is prevented by encasing it over its length in a steel tube filled with mortar (figure 1). The term "Unbonded

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Brace™" derives from the need to provide a slip surface or unbonding layer between the steel core and the surrounding concrete, so that only the steel core resists axial loads. The materials and geometry in this slip layer have been carefully designed and constructed to allow relative movement between the steel element and the concrete, while simultaneously inhibiting local buckling of the steel as it yields in compression. The concrete and steel tube encasement provides sufficient flexural strength and stiffness to prevent global buckling of the brace, allowing the core to undergo fully-reversed axial yield cycles without loss of stiffness or strength. The concrete and steel tube also helps to resist local buckling.

In contrast to the behavior of typical bracing elements, this results in stable hysteretic behavior, which provides a more stable and effective seismic resisting element.

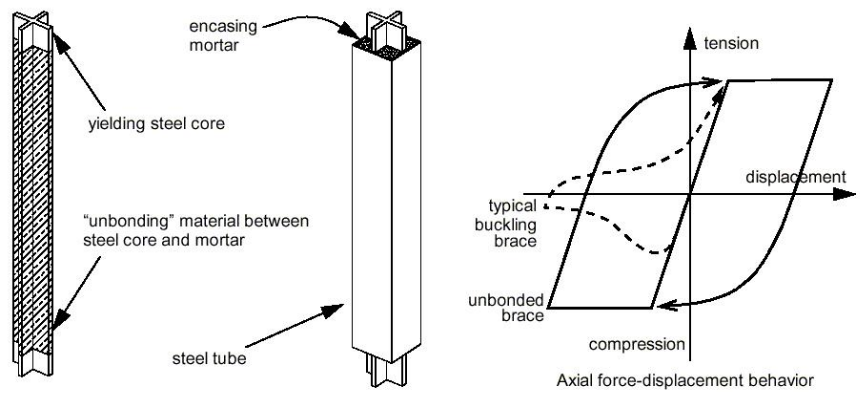


Figure 1. Schematic of Mechanism of Buckling-Resistant Unbonded Braces

Figure 1 Unbonded Brace™ Concept

The brace exhibits nearly identical properties in tension and compression and has the ability to undergo numerous cycles of inelastic deformations without degradation or fracture. Since these braces do not need to be designed to resist buckling, the brace forces are generally lower. This results in lower forces in the superstructure and foundation.

Background

The Unbonded Brace™ has been used on nearly 200 buildings in Japan since 1987. Arup used the Unbonded Brace™ on a number of Japanese projects and recognized the benefit this could bring to the Californian Construction Industry and looked for an opportunity to transfer this technology from Japan to California. This opportunity arose on the UC Davis Plant and Environmental Science Facility in 1999. Arup played a key role facilitating the transfer of this technology from the Japanese researchers and manufacturers to the U.S. market.

As the UBF is a new lateral-force-resisting system, it is not covered by any building code and is therefore classified by the California Building Code as an "Undefined Structural System". Consequently, seismic design criteria, analytical procedures as well as testing programs had to be developed to validate its performance.

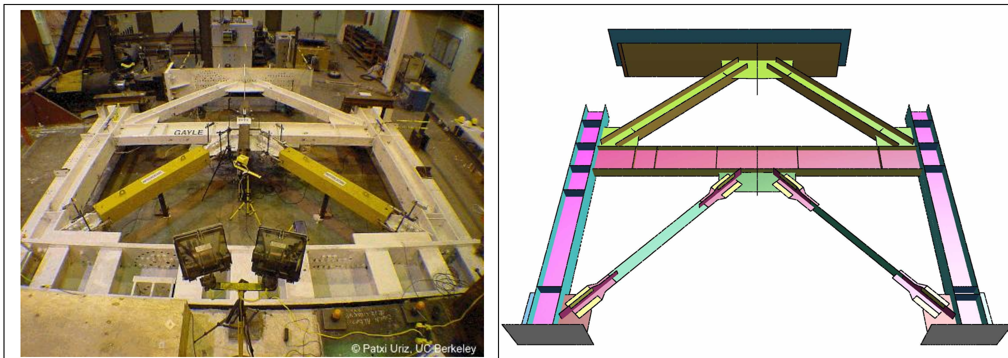
The first tests of the Unbonded Brace™ in the United States were conducted at UC Berkeley during the spring of 1999 and fall of 2000 by Professor E. Popov and Professor N. Makris. On-going research is now being spearheaded by Professor S. Mahin.

The test results demonstrated good performance of the braces under various loading histories specified by SAC protocols.

In parallel, Arup developed numerical models to simulate the behavior of the brace. These showed excellent correlation with the test results.

SIMULATION VALIDATION

Up until last year, only single element testing had been conducted in the US. However, in January 2002, a full-scale test of an Unbonded Braced™ frame was carried out at UC Berkeley by Mahin & Uriz [1] for a project on campus incorporating UBFs (Figure 2(a)). Arup were not involved with the design of this project, but were subsequently asked to simulate the tests. Three frames were tested; one chevron brace configuration and two single diagonal brace configurations. The finite element simulation model is shown in Figure 2(b).



(a) (b)

Figure 2 **(a) UC Berkeley Test Frame** **(b) Arup Finite Element Model**

The implicit solver of LS-DYNA was used by Field [2] for the non-linear pseudo static simulation with excellent results. The benefits of using the implicit solver instead of the explicit solver for this simulation are the reduced run time - 2 hours instead of 24.

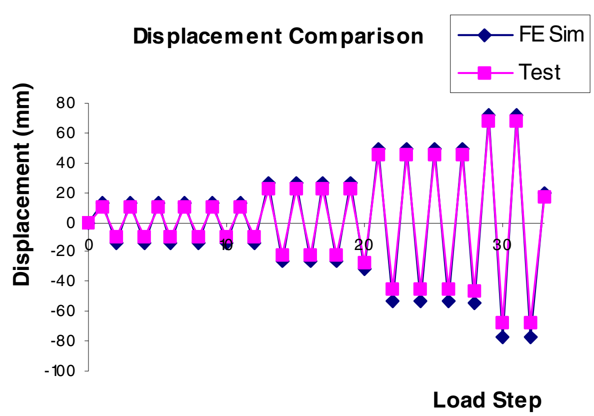


Figure 3 **Comparison of control node displacement**

Figure 3 shows the comparison of test and simulation displacement at the control node (center of left side column panel zone). Figure 4 shows a good match between observed test damage and test simulation yield patterns at the column base stiffener.

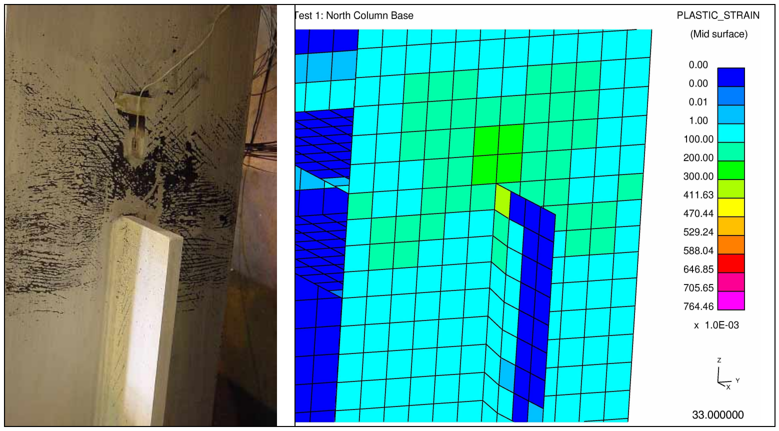


Figure 4 Comparison of observed/simulated damage

KAISER PERMANENTE SANTA CLARA MEDICAL CENTER

Background

The next challenge was the implementation of this technology on a hospital project, as these are reviewed and approved in California by the Office of Statewide Health Planning and Development (OSHPD). Arup had the opportunity to do just this with Kaiser Permanente Santa Clara Medical Center project (Figure 5).

Figure 5 Kaiser Permanente Santa Clara Medical Center

The site is sandwiched between two major fault lines, the San Andreas to the west and the Hayward to the east, so the seismic loads are high and the potential impact of near fault effect is significant.

Currently, there are no code provisions for such frames, so Arup worked closely with OSHPD to set specific design criteria. Arup proposed a dual-level seismic design including both Design Base Earthquake (DBE) and Upper Bound Earthquake. Design (UBE) base shears were established by using un-scaled site-specific response spectra. The seismic system consists of 10 bays of UBFs at each floor in the NS and EW direction.

Frame Simulation

Linear elastic models were assembled for response spectrum analyses of the DBE and UBE. Non-linear dynamic time history analyses were used to determine brace strains and forces for the associated earthquake records. Three pairs of time history records scaled to the site-specific response spectra were used for DBE and UBE. 6 linear and 24 non-linear time history analyses were performed per frame. The non-linear dynamic time history analyses were performed using the explicit time integration software, LS-DYNA, which we co-develop.

Having verified the implicit simulation solution procedure with the Berkeley frame test data it was used to assess local behavior for the BRBFs on the Kaiser project. A full finite-element model of both chevron and single diagonal BRBF configurations were constructed and virtually tested as shown in Figure 6 below.

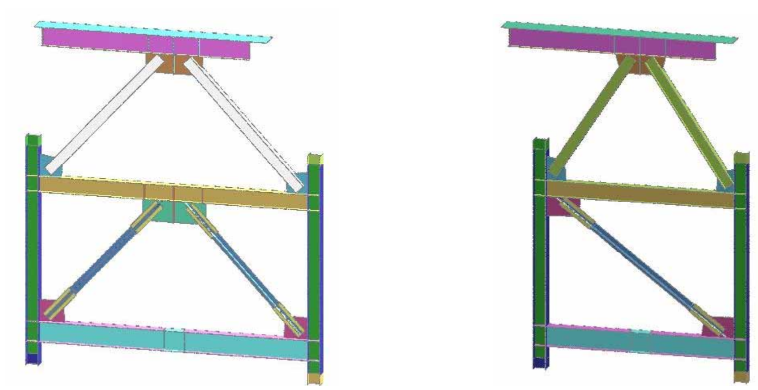


Figure 6 Chevron and Diagonal Unbonded Braced Frame Configurations

Steel plastic strain (yielding) for various drift levels is shown below in Figures 7 and 8 for the diagonal and chevron configuration respectively.

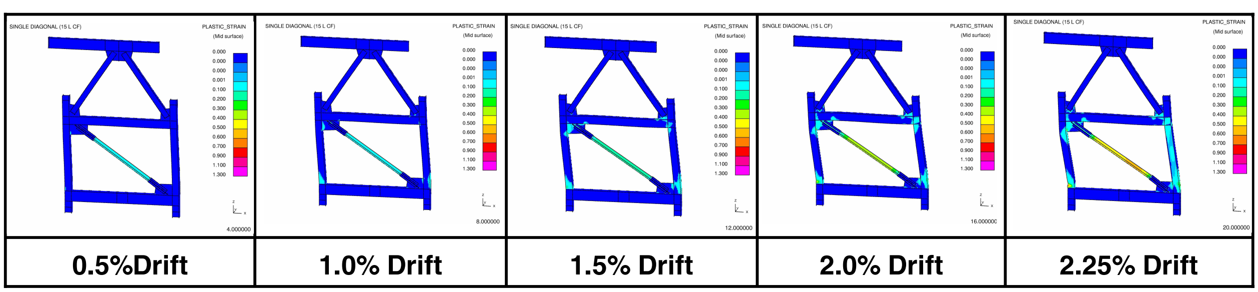


Figure 7 Plastic Strain at various drift levels for diagonal configuration

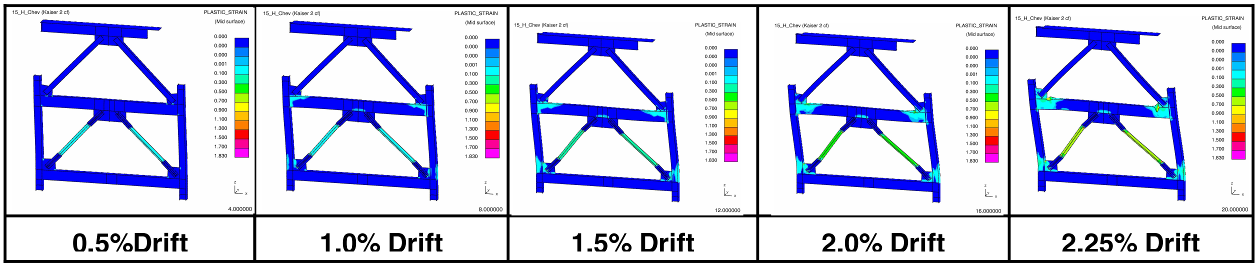


Figure 8 Plastic Strain at various drift levels for chevron configuration

These virtual test simulations show that current connection detailing results in considerable yielding and concentrated stresses at connections at drifts at and above 1.5%, which in turn place limits on the performance of the frame. The BRB performs well throughout. Figure 7 shows extensive gusset plate yielding at 2.25% drift, with a “hotspot” at the column/plate weld, which could lead to fracture.

The chevron arrangement (figure 8) is more forgiving, as the central beam/brace connection provides more flexibility for the frame movement. The single diagonal arrangement has higher strains since the lateral force is concentrated through one gusset plate connection and because of plate pinching between the beam and column as the frame sways.

For the Kaiser Santa Clara project we controlled this issue by using the chevron arrangement and limiting the drift to 1.25% during a DBE event and 2.25% for a UBE event.

CONNECTION PERFORMANCE

The original gusset plate shown in figure 9(a) was ¾” thick and designed accordingly to standard practice. High levels of yielding were observed in the connection (shown in figure 9(b)) with a high stress concentrate on at the weld, which could lead to fracture concerns.

A series of simulations were undertaken to investigate this issue. Various connection configurations and thicknesses were considered, as shown below in figures 9 through 13.

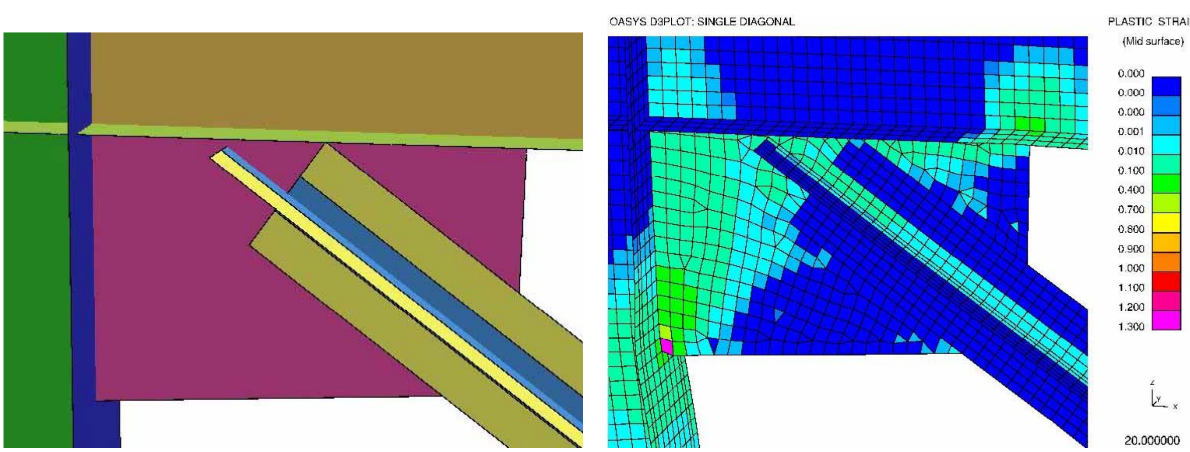


Figure 9 (a) Gusset Plate Geometry (b) Plastic Strain

Thickening the plate to 1” was considered, producing the results in figure 10. This greatly reduced the strain in the plate, but the additional connection stiffness attracted more load in to the frame, thereby causing additional yielding in the beams and columns. To offset this effect, the gusset plate size was reduced (figure 11a), giving the improved plastic strain results seen in figure 11(b).

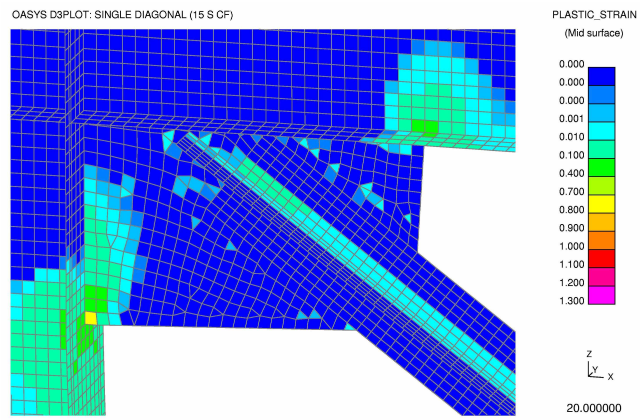
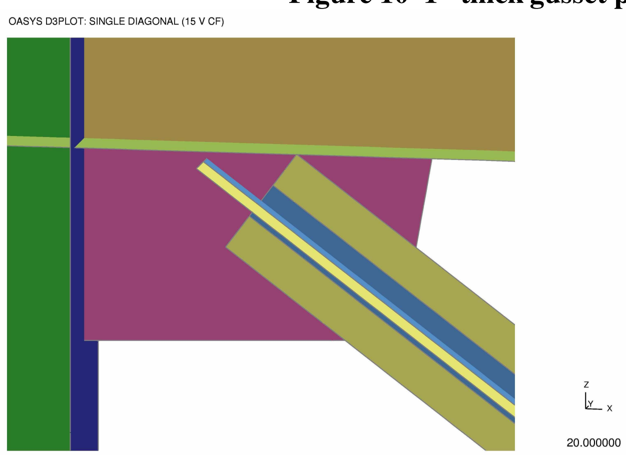


Figure 10 1" thick gusset plate strain @ 2.25%



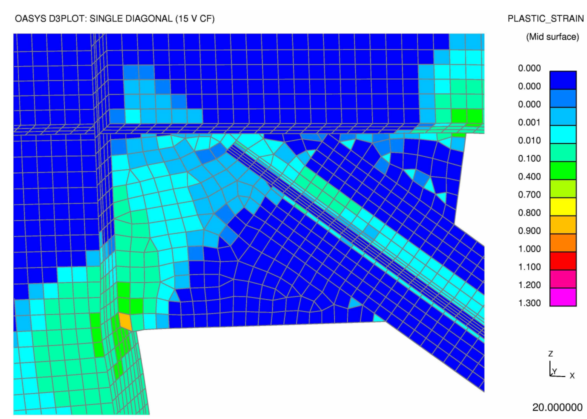


Figure 11   **(a) 1" plate revised geometry**   **(b) Plastic Strain @ 2.25% drift**

For similar arrangements, we would not recommend gusset plates thinner than ¾" as our simulations have indicated plate buckling problems, which lead to out-of-plane instability of the BRB.

We next investigated the effect of adding plate stiffeners, looking at various configurations.

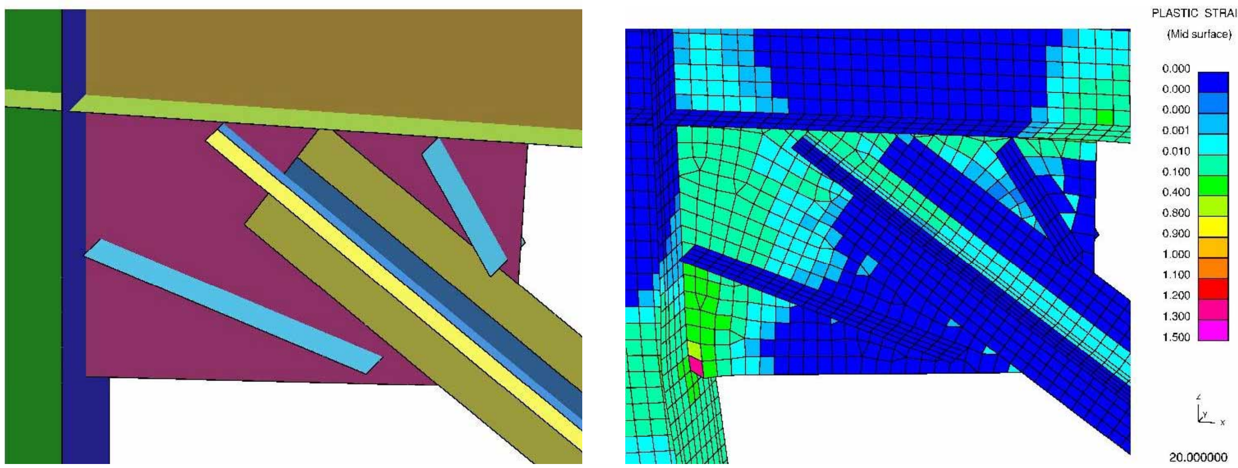


Figure 12 (a) ¾"gusset plate with stiffeners (b) plastic Strain @ 2.25% drift

While these stiffeners may be useful for preventing buckling, in the cases studied, they made no impact on the extent of yielding in the plate and did, in fact, increase the strain at the weld (figure 12(b)).

The final study looked at reducing the stress concentration in the gusset plate by modifying the shape at the column weld. This is shown in figure 13(a).

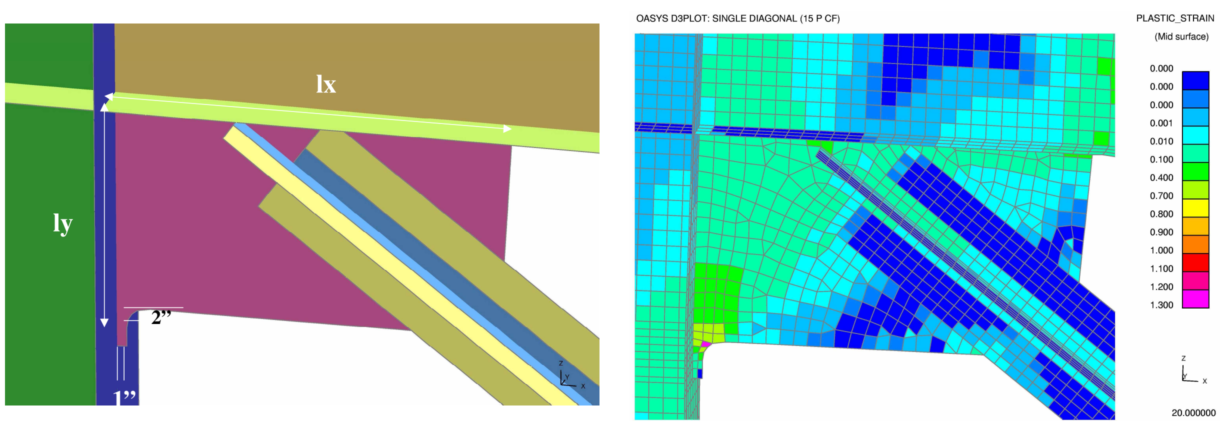


Figure 13 (a) ¾" gusset with curved detail (b) plastic strain @ 2.25% drift

Figure 13(b) shows that the curved detail is very effective at decreasing the strain at the weld, producing a reduction of 50%.

It should be noted that this level of gusset plate yielding and concerns over weld fracture are not just related to a buckling restrained brace frame – any frame that has a similar connection will have these issues – i.e. this in no way suggests that buckling restrained braced frames are unreliable. It has been shown by Ko et al [3,4,5] that the BRB is a more stable and effective seismic system than other traditional frames such as CBFs and EBFs, where similar connection performance issues also need to be addressed.

CONCLUSION

The buckling restrained brace frame is an excellent seismic resisting system. Actual tests by Mahin & Uriz [1] and SIE [6] and simulated tests by Ko and Field [2,3] have shown that the performance of the buckling restrained brace is not in question. However, these same tests have highlighted the importance of the connection between the brace and the frame. The stiffness of this connection affects the behavior of the frame – stiffer connection cause more force in the beams and columns. The size and thickness of the plate affects the extent of yielding in the plate and the concentrated stresses at the welds. The stiffness and strength of the connection can be optimized by changing the thickness and shape of the plate. Reshaping the plate and introducing some curvature, as indicated in this paper, can significantly reduce the concentrated stresses at the weld. If these measures cannot be implemented, frame drifts can be limited by design to ensure that excessive gusset yielding does not occur.

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