Steel Structures Research Update

Strongback Steel-Braced Frames for Improved Seismic Behavior in Buildings

JUDY LIU

INTRODUCTION

Ongoing work on the strongback braced frame is highlighted. The research is led by Dr. Stephen Mahin, professor at the University of California–Berkeley, and Byron L. and Elvira E. Nishkian, professors of structural engineering. Dr. Mahin currently leads the SimCenter as part of the Natural Hazards Engineering Research Infrastructure (NHERI) and was recently awarded an AISC grant to research and develop a possible design method for the strongback system.

There have been a number of investigations and examples of implementation of the strongback system in recent years. Dr. Jiun-Wei Lai, an engineer at Degenkolb Engineers in California, compared the behavior of strongback systems with conventional braced-frame systems through monotonic, cyclic, and nonlinear dynamic time-history analyses as a doctoral student at the University of California–Berkeley (Lai and Mahin, 2015). Barbara Simpson, a doctoral candidate at U.C. Berkeley, conducted the first experimental test of a strongback system (Simpson and Mahin, 2016) and is currently focused on developing the strongback system. In tandem, a strongback buckling restrained braced frame (BRBF) was constructed by Tipping Structural Engineers in Berkeley, California, and tested under quasi-static cyclic loading at U.C. Berkeley (Panian et al., 2015). Modified versions of the strongback have also been employed by Gregory P. Luth & Associates for several buildings on the West Coast as well as throughout the Central United States over the past 6 years (Luth, 2017). Pollino et al. (2017) have more recently studied and conducted hybrid testing (Slovenec et al., 2017) on the Stiff Rocking Core (SRC), a rehabilitation scheme utilizing conventional buckling and yielding brace behavior. Related work on rocking and self-centering braced frames has been conducted by Eatherton et al. (2014), Sause et al. (2014), and others.

Similar resisting systems have been studied internationally. In Canada, a dual system utilizing a pinned-base vertical elastic truss has been investigated by Tremblay et al. (1997) to mitigate soft-story response in tension-only braced frames and, later, buckling restrained brace (BRB) frames (Tremblay, 2003; Tremblay and Merzouq, 2004; Tremblay and Poncet, 2004; Merzouq and Tremblay, 2006). In the 1990s, Japanese researchers also studied spine systems with elastic trussed stems coupled with BRBFs to mitigate damage concentration, and the concept was applied in a 24-story building in Tokyo (Aoki et al., 1998; Taga et al., 2004). The contribution of a vertical elastic spine has similitudes with the role played by an ancient Japanese pagoda's central column (shinbashira) in controlling floor sways to prevent seismic collapse (Nakahara et al., 2000). In Japan, researchers have also proposed an elastic truss system with BRB fuses (Takeuchi and Suzuki, 2003; Takeuchi et al., 2015), a concept also studied by Tremblay et al. (2004) and Wu and Lu (2015) in China. Retrofit of seismically deficient structures with stiff rocking walls was initially proposed and implemented in Japan (Wada et al., 2009; Qu et al., 2012). A continuous column concept with gravity columns distributing demands from weak or soft stories at adjacent stories was studied in Canada (Tremblay and Stiemer, 1994; Tremblay, 2000), New Zealand (MacRae et al., 2004; MacRae, 2011), and Japan (Ji et al., 2009). In Canada, minimum column continuity requirements have been implemented for seismic design of multistory steel-braced frames (CSA, 2001). For eccentrically braced steel frames (EBFs), Martini et al. (1990) proposed to vertically tie the links to achieve more inelastic demand in links. The resulting tied-EBF consisted of two elastic trussed masts pinned at their bases and interconnected by a series of ductile links. The structural system was further examined by researchers from Italy (Ghersi et al., 2000, 2003; Rossi, 2007). Researchers in Canada proposed to divide the tied-EBF masts in pin-connected modules to reduce the force demands on the truss members while preserving the beneficial drift concentration mitigating effect (Chen et al., 2012; Tremblay et al., 2014).

STRONGBACK CONCEPT

While current AISC provisions have greatly improved the seismic behavior of conventional braced frame systems, they still have a tendency to form weak stories (e.g., Uriz

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and Mahin, 2008; Khatib et al., 1988; Tremblay and Poncet, 2004) (Figure 1a). The strongback system was developed as a method of delaying or preventing weak-story behavior. Conceptually, the inclusion of an "essentially elastic" backbone, or strongback, enforces a nearly uniform drift distribution, thereby engaging adjacent stories upon the initiation of inelastic behavior in the opposite braces (Figure 1b). In this sense, the bay of a conventional braced frame is designed to be asymmetric with both an inelastic, energy dissipation portion and an essentially elastic, distributed deformation demand portion.

A variety of different strongback or elastic truss configurations can be utilized. Options based on Simpson and Mahin (in press), Slovenec et al. (2017), and Merzouq and Tremblay (2006) are shown in Figure 2. The elastic portion of the frame could be a truss or, alternatively, a concrete or steel plate shear wall. The elastic portion is often pinned at its base and is not intended to increase lateral strength but, instead, to supply a means of transferring demands vertically between stories. Vertical ties or connecting elements are required to transfer forces. The inelastic portion of the frame could be buckling restrained braces (BRBs) or conventional yielding and buckling brace members.

The strongback provides an economical means of engaging both the strength and energy absorption capacity of an entire system and averaging damage over the height of the building. Peak inelastic demands and damage are reduced. Further, the ability of the strongback to bridge across and distribute forces over multiple stories allows for removal of braces at some stories, as shown in Figure 2a. As noted by Panian et al. (2015), the backbone may require extra strength to remain elastic, but cost savings can be found in use of "ordinary details in the elastic truss, the utilization of the same brace cross section and connection details at every story, and a reduction of the strength or number of braced frames if a reduced redundancy factor could be justified" (Simpson and Mahin, 2016).

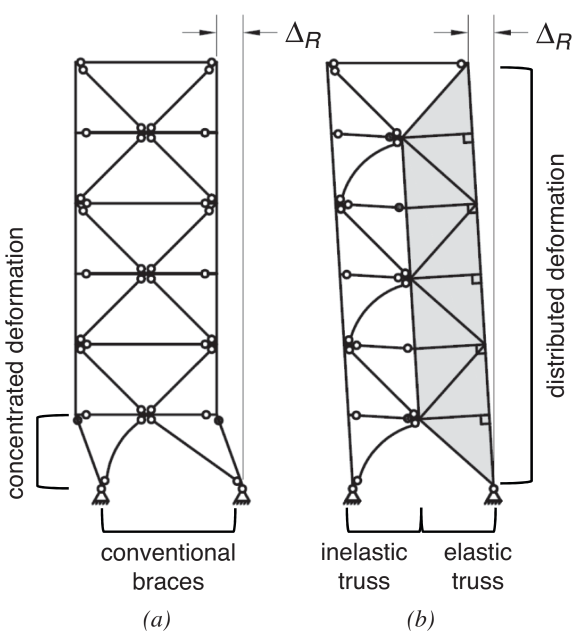


Fig. 1. Comparison of (a) conventional and (b) strongback braced frames (courtesy of Barbara Simpson).

RESEARCH AND PRACTICE

The strongback has been utilized in both research and practice. Previous numerical investigations of strongback behavior have focused on nonlinear time-history analyses. A strongback retrofit was also tested experimentally as an extension of research on older concentrically braced frames. This preliminary work has shown that the strongback method could be a viable method of resisting a weak-story response. The design and construction of several buildings with strongback frames has shown that this system also has the potential of being integrated into current design practice.

Past Numerical Studies

Numerical investigations into strongback and similar systems include work by Lai and Mahin (2015) and Merzouq and Tremblay (2006). Both studies compared conventional systems and strongback or elastic truss systems.

Merzouq and Tremblay (2006) compared the performance of five prototype office buildings ranging from 8 to 24 stories and located in Victoria, British Columbia. Three different configurations were studied for each prototype building: chevron bracing with BRB members, chevron bracing with BRBs and elastic trusses split between two exterior bays, and a two-story X-bracing configuration with a central elastic truss (Figure 2c). Nonlinear, dynamic time-history analyses were conducted for two suites of ground-motion records. One suite included four simulated and six historical ground-motion time histories typical of the Victoria region at magnitude 6.5 and magnitude 7.2. The second suite was comprised of four ground-motion time histories simulated for magnitude 8.5 rupture scenarios along the Cascadia subduction fault plane. "The ground motion amplitude was adjusted to match, on average, the 2% in 50 year probability of exceedance spectrum over the applicable period range" (Merzouq and Tremblay, 2006).

The analysis results highlighted the potential of the elastic truss, or "dual BRB," system and the shortcomings of the conventional chevron configuration with BRBs. Despite the stable hysteretic response of the BRBs, failure of the conventional BRB frames occurred for some of the Victoria ground motions and for all of the Cascadia ground motions. "These structures experienced large story drifts and several occurrences of dynamic instability were observed, indicating that the frames did not possess sufficient capacity to redistribute the inelastic demand over their height" (Merzouq and Tremblay, 2006). By contrast, collapse of the dual BRB system occurred only for the 12-story prototype for one of Cascadia ground motions. "However, even in that case, all members of the elastic truss remained elastic, as was also the case under all other ground motions, confirming the adequacy of the proposed empirical design rules" (Merzouq and Tremblay, 2006). The empirical design rules included first designing the BRBs for the code-specified forces, conducting capacity design for all other members, and determining forces in the elastic truss according to stiffness of the elastic truss and expected variation between floors for the expected BRB plastic deformations. Further investigation of the empirical design approach is needed to confirm efficacy with respect to performance objectives, other building heights, and other frame geometries.

Lai and Mahin (2015) investigated six different configurations, including a typical chevron brace configuration, a typical two-story X-bracing configuration (model X6; Figure 3a), and an offset two-story X-bracing configuration with the intersection of the braces at a third point of the beam (model X6-3; Figure 3b). They also studied an offset two-story X-bracing configuration with conventional braces

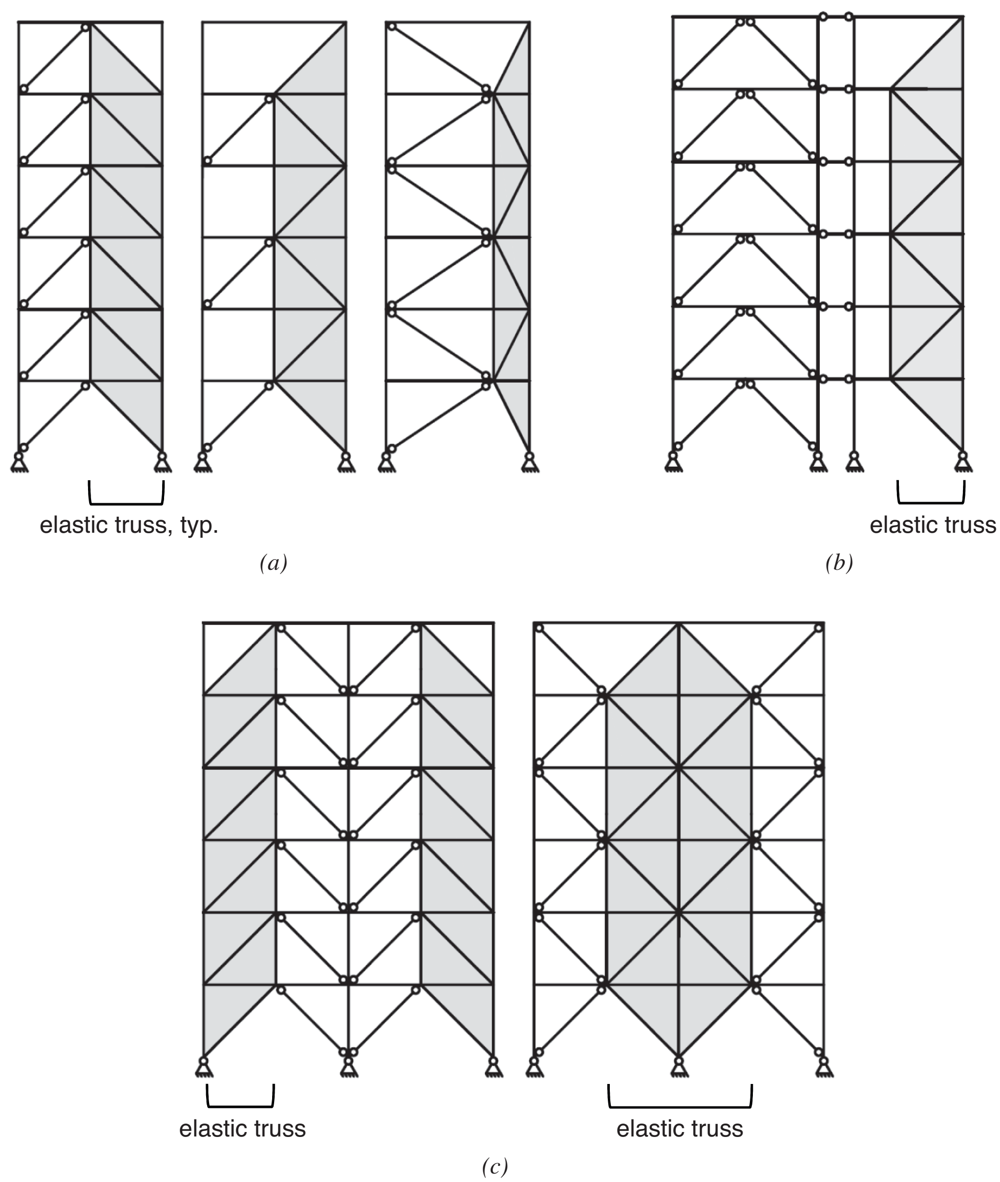


Fig. 2. Possible strongback or elastic truss system configurations based on (a) Simpson and Mahin (in press), (b) Slovenec et al. (2017), and (c) Merzouq and Tremblay (2006) (courtesy of Barbara Simpson).

and vertical strongback "spines" (model SB6-3; Figure 3c). Additional variations included the use of BRB braces with standard and low-yield steel in the cores. A pair of braced bays was located on each side of the five-by-five bay, six-story office prototype building.

Highlighted here are models X6, X6-3 and SB6-3 (Figure 3). Lai and Mahin (2015) utilized an overstrength factor approach for design of the strongback spines, conducted nonlinear time histories on the prototype buildings, and compared the performance of the conventional and strongback braced frames. Model X6 exhibited somewhat fewer concentrated deformations compared to the chevron frame, with higher story drift ratios observed in two-story panel mechanisms. The concentration of deformation was reduced further with model X6-3. However, it was model SB6-3 that successfully prevented localized concentration of story deformation. The behavior of model X6-3 was as expected; most of the strongback spine braces remained elastic, and braces outside of the spines buckled. Lai and Mahin (2015) noted that the "design optimization of this simple strategy should be studied further"; the use of the overstrength factor did not fully account for physical behavior, force redistributions, and resulting demands on the strongback spines.

Large-Scale Experimental Study

Building upon the computational studies to date, a large-scale experimental investigation explored the viability of the strongback system under cyclic loading and its ability to mitigate weak-story behavior (Simpson and Mahin, 2016; Simpson et al., in press). The two-story, one-bay specimen was a nearly full-scale frame and included a BRB and a strongback with conventional HSS braces (Figure 4). This specimen represented a possible retrofit scheme for a conventional chevron braced frame, two of which were also tested in the experimental program. The original chevron braced frame (NCBF-B-1) was designed to older code standards, did not satisfy current seismic provisions, and formed a weak story after severe brace local buckling and fracture. A second chevron braced frame (NCBF-B-2) had braces filled with low-strength concrete to delay local buckling, but it also experienced brace local buckling and fracture, yielding in the first story beam, and a weak story. For the retrofit, new braces and gusset plates were oriented in a strongback configuration (NCBF-B-3SB). The original beam and column sizes were kept the same as the older braced frame tests. The column, HSS braces, and right half of the beam formed the elastic strongback. The BRB on the left side of the frame was intended as the primary energy-dissipating element, and the strongback brace members were sized based on the maximum forces that the BRB could deliver to the rest of the frame. Plastic hinging was expected at both column bases; the right (strongback) column base was oriented for bending about the weak axis to better simulate a "pinned" base. Inelastic behavior was also expected in the left half of the first-story beam, acting as a sort of shear link; the web of the original beam was reinforced with doubler plates at the gusset plate connection. No inelastic brace was required in the second story because the strongback was able to engage the entire system.

The test specimen was subjected to quasi-static loading, following a testing protocol similar to cyclic qualification procedures for BRBs (AISC, 2016). Displacement was applied at the roof beam; a force equal to half of the load at the roof was applied at the first-story beam. The strongback successfully mitigated weak-story formation and was able to maintain nearly uniform drift over both stories for the entire loading history. The uniform drift for NCBF-B-3SB is demonstrated in Figure 5. In this figure, the ratio of first-story drift (Δ_1) to total drift ($\Delta_1 + \Delta_2$) remains at approximately 50% for the duration of the test. This is contrast to specimens NCBF-B-1 and NCBF-B-2, which deviate from 50% with the onset of local buckling (LB) of the braces, indicating weak-story formation.

The strongback specimen did experience a reduction in strength and stiffness after local buckling of the BRB casing in a cycle to a roof drift of 2.5%, but it continued to exhibit stable hysteresis loops (Figure 6) and to resist forces in compression after rupture (noted as F_r in Figure 5). The BRB did satisfy current cyclic testing requirements for BRBs (AISC, 2016) prior to rupture. As expected, plastic hinges did form

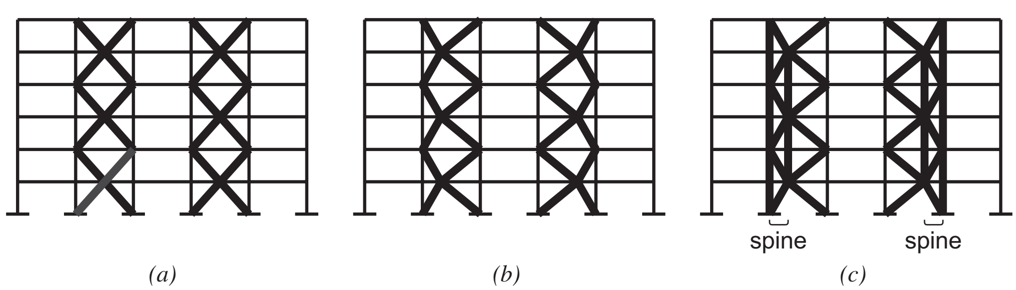
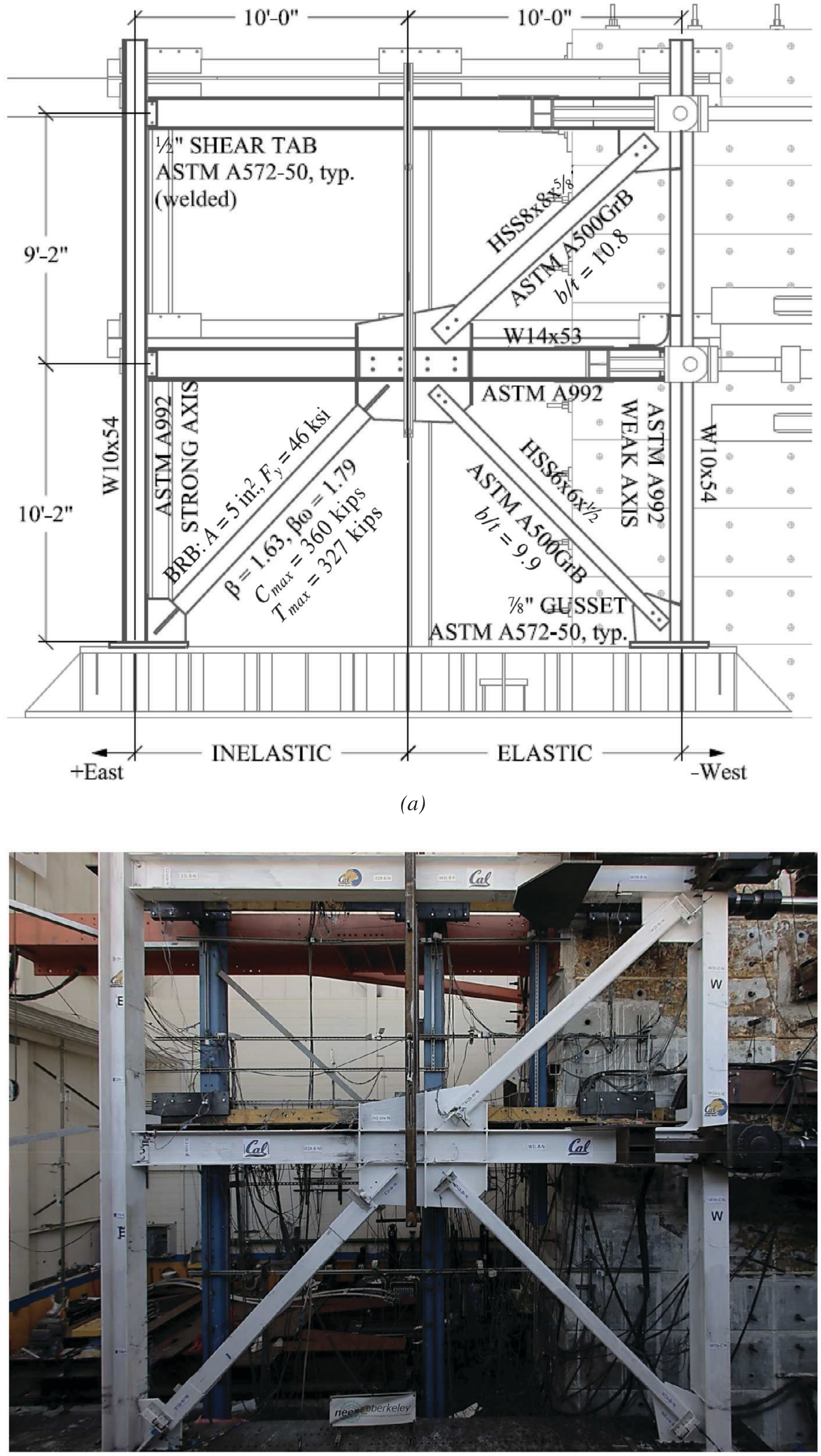


Fig. 3. (a) Conventional two-story X-bracing frame, (b) offset two-story X-bracing frame, and (c) offset two-story X-bracing with vertical strongback spines (based on Lai and Mahin, 2015).



(a)

(b)

Fig. 4. (a) Schematic and (b) photo of strongback test specimen (courtesy of Barbara Simpson).

at the column bases and in the first-story beam to the left of the gusset plate. Residual drift was similar in both stories. The inelastic demands were significant in some cases; current research is investigating an offset bracing scheme designed to decrease these inelastic demands while limiting the demands developed in the strongback. The strongback braces, meanwhile, remained essentially elastic. Figure 6 shows predictable behavior through comparisons of numerical simulations and NCBF-B-3SB experimental results for base shear versus roof drift ratio and BRB axial force versus deformation. In the numerical model, the braces were able to buckle out of plane, and the BRB element included a low-cycle fatigue material model (Uriz and Mahin, 2008).

Implementation in Practice

Strongback frames have been used for the seismic-force-resisting systems in a number of buildings in recent years. Different versions of the strongback have been explored, including a buckling restrained braced mast (BRBM) frame, a rocking frame, and a pivoting frame.

Tipping Structural Engineers designed a buckling restrained braced mast (BRBM) frame for the four-story Heinz Avenue Building in Berkeley, California (Panian et al., 2015). The BRBM for this laboratory building utilized wide-flange shapes in a vertical truss, or mast, and BRBs for the yielding elements (Figure 7). The same BRB size could

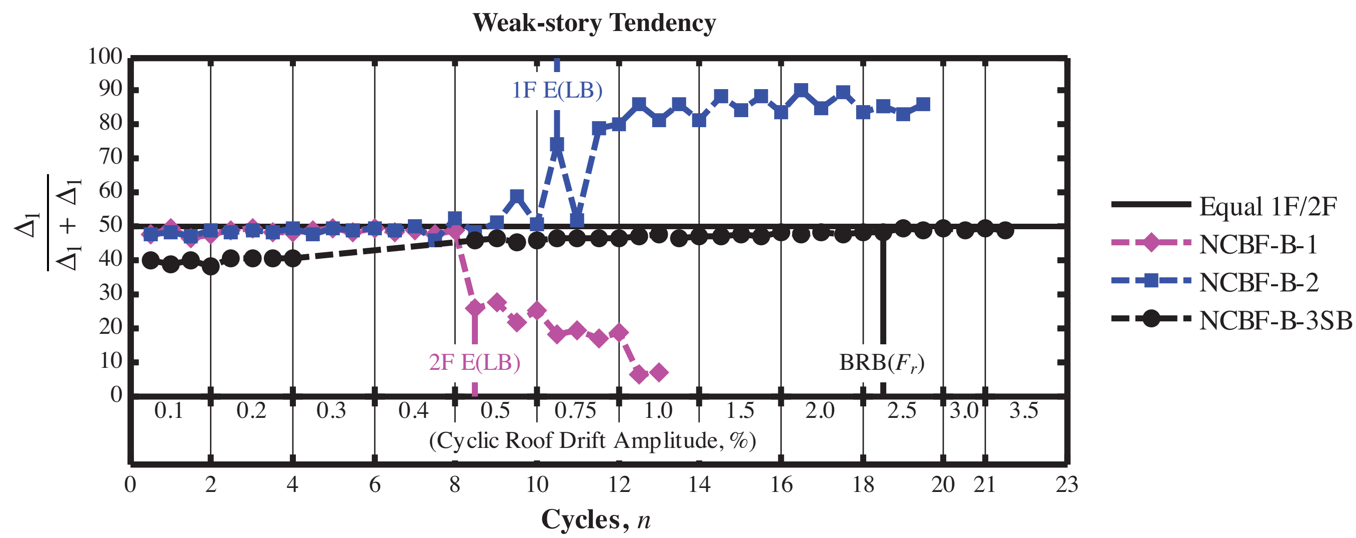


Fig. 5. Weak-story tendencies in braced frame tests (courtesy of Barbara Simpson).

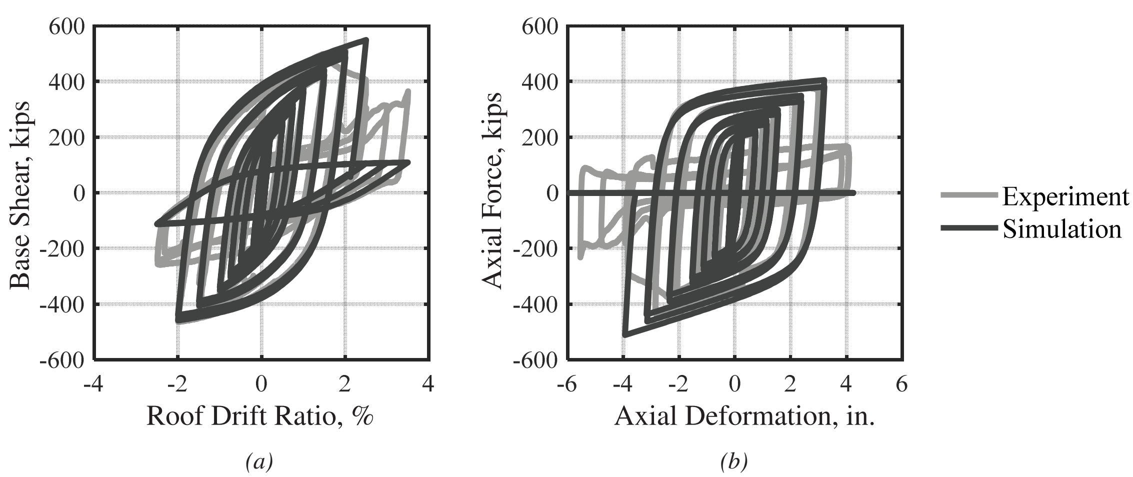
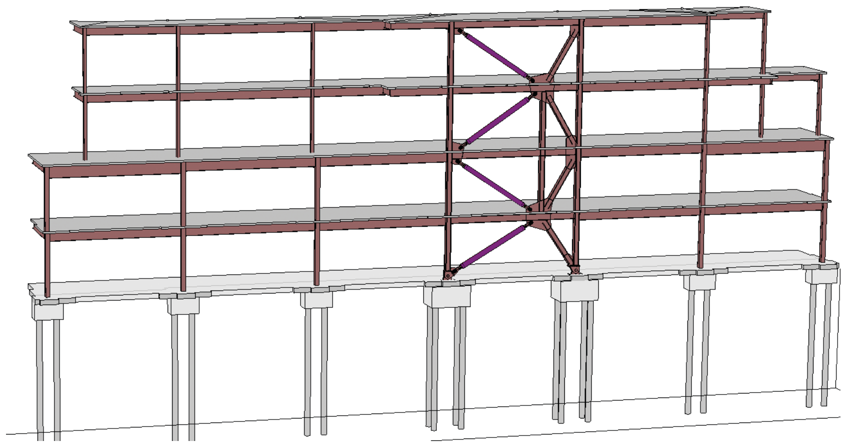


Fig. 6. Comparisons of experimental versus numerical simulation results for strongback frame: (a) base shear versus roof drift ratio; (b) BRB axial force versus deformation (courtesy of Barbara Simpson).



(a)

(b)

Fig. 7. (a) Elevation drawing and (b) photograph of BRBM frame in the Heinz Avenue building under construction (images courtesy of Tipping Structural Engineers).

be used at all stories because of the mast's ability to engage all stories to resist any additional-story shear, thus preventing a soft-story mechanism. Pinned column bases were used to reduce local bending and foundation loads. The BRBM utilized an offset geometry, as shown by Lai and Mahin (2015), to help to reduce inelastic demands.

The mast in the BRBM was designed to remain elastic for the design basis earthquake. Nonlinear time-history analysis, capacity design principles, and an overstrength factor of 2.0 were used. The overstrength factor was validated against forces obtained through a redundancy analysis; removal of a brace at any level did not result in more than a 33% reduction in story shear capacity or extreme torsional irregularity. The redundant BRBM used less than a third of the BRBs and approximately half of the number of frames as a conventional BRB frame.

Gregory P. Luth & Associates designed a number of modified rocking frames with essentially elastic strongbacks over the past 6 years. Their frames utilize either a "rocking" system, with columns lifting up in a rocking motion, or a "pivoting" frame that rotates around a pin at its base. Says Luth, "the latter may result in less non-structural damage as it does not involve differential movement at the floors." In 2011, post-tensioned shop-fabricated frames created a self-centering rocking frame system for a casino in Cape Girardeau, Missouri, at a site with ground motions comparable to those of San Francisco. "Krawinkler fuses" (Figure 8c) provided connections between the rocking frames and 10-ft-deep shop-fabricated trusses to dissipate energy. In 2014, a pivoting frame with a buckling restrained column (BRC) on one side and true pin on the other side was used in a casino in Jamul, California. After yielding of the BRC, "additional overturning resistance is provided by a full-story vierendeel frame at the top floor with Krawinkler fuses as the shear connection at the center of the vertical members of the vierendeel" (Luth, 2017).

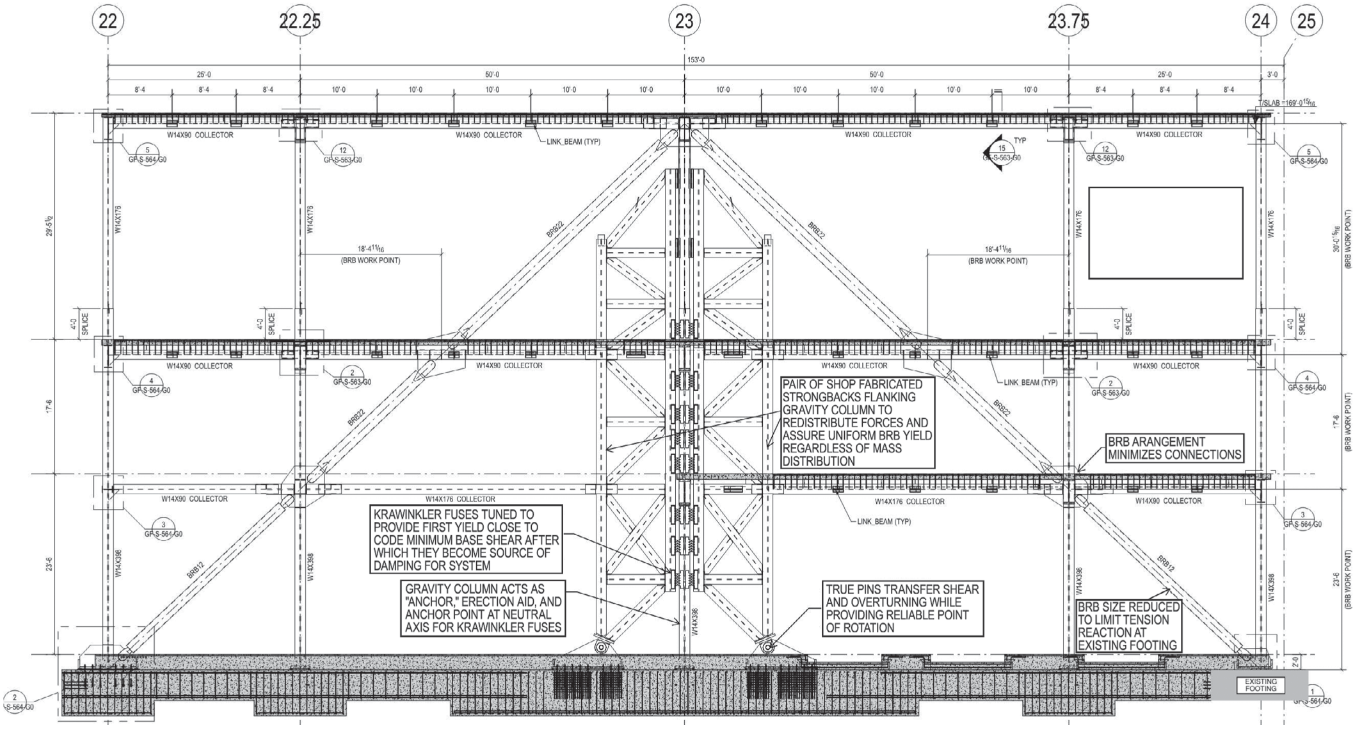
In 2016, the Tesla Gigafactory in Reno, Nevada, presented a challenge with a fast-paced design for "potential equipment loads of up to 250 psf and 350 psf on the 2nd and 3rd floors respectively although actual loading was not defined until after steel fabrication had started (i.e. vertical mass distribution was undefined at the structural design phase)" (Luth, 2017). To economically accommodate significant variations in vertical mass distribution, Luth, working with nonlinear time histories and pushover analyses by Exponent, developed a pivoting strongback system. A pair of pinned-base, shop-fabricated frames flanking and connected to gravity columns with Krawinkler fuses (Figure 8) provide approximately 20% of the seismic resistance; the rest is provided by buckling restrained braces. Luth notes that the BRBs and the Krawinkler fuses "are forced to yield more or less uniformly by the strongback which remains elastic. Because of the redistribution function of the strongbacks, we are able to 'tune' the brace areas for things other than strength. We can distribute the overturning moment across multiple columns by manipulating the brace area. The braces are effective no matter where you put them as long as you provide collectors to transfer the required forces. Conceptually, you could [place] all the braces at the top floor, the middle floor, or the bottom floor and there would be a complete load path. Of course the demands on the strongback change dramatically with these three basic arrangements. We found that the most efficient strategy was to use heavier BRB's in the middle story rather than the top or bottom. The most efficient arrangement ended up being a single full height chevron which creates a 'guyed' strongback arrangement" (Luth, 2017).

BEHAVIOR AND DESIGN OF STRONGBACK SYSTEMS

While there has been a variety of work on the strongback system in both research and practice, these analyses and design methods have depended largely on the use of iterative, nonlinear time-history analyses. These investigations have not indicated that a simple and reasonable design methodology exists that can robustly be extended to any generalized building system. Thus, research has focused on the development of a design methodology that can be simply and easily applied in practice. The current objectives of this research include:

1. Clarify which parameters influence the behavior of the strongback.
2. Develop a simple and coherent design methodology for the strongback system.
3. Validate the effectiveness of potential design, proportioning and detailing guidelines.
4. Present refined design methods to address enhanced performance objectives.

Requirements for the relative strength of the essentially elastic strongback to the strength of the inelastic bracing elements and the use of a redundancy factor is currently being studied. Parametric studies will be used to determine effects of various story heights and number of stories. Future work also includes investigation of alternative bracing configurations, types of inelastic braces (e.g., buckling restrained braces versus conventional brace members with buckling and yielding), and the effects of vertical or mass irregularities. Detailing of critical regions, such as the column base and of the strongback to inelastic frame connections, is also warranted. Finally, a cost–benefit analysis and performance evaluation is necessary to quantify the strongback's repair time and repair cost compared to conventional bracing



(a)

(b)

(c)

Fig. 8. (a) Elevation drawing and (b) photograph of strongback frame for the Tesla facility; (c) Krawinkler fuses (images courtesy of Gregory P. Luth & Associates).

systems. Validation through future experimental testing utilizing a strongback would confirm the effectiveness of the developed design method.

SUMMARY

The viability of the strongback braced frame has been demonstrated through computational parametric studies and experimental investigations. The strongback frame is able to engage multiple stories and eliminate weak-story behavior, resulting in improved seismic performance. Variations—from a buckling restrained braced mast (BRBM) to a pivoting, guyed strongback frame—have been implemented in buildings in high seismic regions, typically at a cost savings compared to conventional BRB frames. To date, each study or implementation has utilized its own combination of nonlinear time-history analyses and capacity design principles. Ongoing research is focused on developing a simple and coherent design methodology for the strongback braced frames.

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REFERENCES

AISC (2016), "Seismic Provisions for Structural Steel Buildings," ANSI/AISC-341-16, American Institute of Steel Construction, Chicago, IL.

Aoki, K., Fukuyama, K., Okumoto, H., Ukai, K. and Taga, K. (1998), "Design of a High-Rise Building Using Unbonded Braces with Varying Cross Section," *Journal of Construction Steel*, Vol. 6, pp. 139–144 (in Japanese).

Chen, L., Tremblay, R. and Tirca, L. (2012), "Seismic Performance of Modular Braced Frames for Multi-Storey Building Application," 15th World Conference on Earthquake Engineering, Lisbon, Portugal, Paper No. 5458.

CSA (2001), "CSA/CAN-S16-01, Limit States Design of Steel Structures," Canadian Standards Association, Toronto, ON.

Eatherton, M., Ma, X., Krawinkler, H., Mar, D., Billington, S., Hajjar, J. and Deierlein, G. (2014), "Design Concepts for Controlled Rocking of Self-Centering Steel-Braced Frames," *Journal of Structural Engineering*. ASCE, Vol, 140, No. 11.

Ghersi, A., Neri, F., Rossi, P.P. and Perretti, A. (2000), "Seismic Response of Tied and Trussed Eccentrically Braced Frames," *Proceedings of the STESSA 2000 Conference*, Montreal, Canada, pp. 495–502.

Ghersi, A., Pantano, S. and Rossi, P.P. (2003), "On the Design of Tied Braced Frames," *Proceedings of the STESSA 2003 Conference*, pp. 413–429.

Ji, X., Kato, M., Wang, T., Hitaka, T. and Nakashima, M. (2009), "Effect of Gravity Columns on Mitigation of Drift Concentration for Braced Frames." *Journal of Construction Steel Research*, Vol. 65, No. 12, pp. 2148–2156.

Khatib, I.F., Mahin, S.A. and Pister, K.S. (1988), "Seismic Behavior of Concentrically Braced Frames," Report UCB/EERC-88/01, Earthquake Engineering Research Center, University of California, Berkeley, CA.

Lai, J. and Mahin, S.A. (2015), "Strongback System: A Way to Reduce Damage Concentration in Steel-Braced Frames," *Journal of Structural Engineering*, ASCE, Vol, 141, No. 9.

Luth, G. (2017, June 13), Email with J. Liu.

MacRae, G.A. (2011), "The Continuous Column Concept—Development and Use," *Proceedings of the 9th Pacific Conference on Earthquake Engineering*, Auckland, New Zealand, Paper No. 83.

MacRae, G., Kimura, Y. and Roeder, C. (2004), "Effect of Column Stiffness on Braced Frame Seismic Behavior," *Journal of Structural Engineering,* ASCE, Vol. 130, No. 3, pp. 381–391.

Martini, K., Amin, N., Lee, P.L. and Bonowitz, D. (1990), "The Potential Role of Non-Linear Analysis in the Seismic Design of Building Structures," *Proceedings of the 4th U.S. National Conference on Earthquake Engineering,* pp. 67–76.

Merzouq, S. and Tremblay, R. (2006), "Seismic Design of Dual Concentrically Braced Steel Frames for Stable Seismic Performance for Multi-Story Buildings," *Proceedings of the 8th U.S. National Conference on Earthquake Engineering*, San Francisco, CA.

Nakahara, K., Hisatoku, T., Nagase, T. and Takahashi, Y. (2000), "Earthquake Response of Ancient Five-Story Pagoda Structure of Horyu-Ji Temple in Japan," *Proceedings of the 2000 WCEE*, Paper No. 1,229.

Panian, L., Bucci, N. and Janhunen, B. (2015), "BRBM Frames: An Improved Approach to Seismic-Resistant Design Using Buckling-Restrained Braces." *Second ATC & SEI Conference on Improving the Seismic Performance of Existing Buildings and Other Structures*, December 10-12, ASCE, San Francisco, CA, pp. 632–643.

Pollino, M., Slovenec, D., Qu, B. and Mosqueda, G. (2017), "Seismic Rehabilitation of Concentrically Braced Frames Using Stiff Rocking Cores," *Journal of Structural Engineering*, ASCE, Vol. 14, No. 9.

Rossi, P.P. (2007), "A Design Procedure for Tied Braced Frames," *Earthquake Engineering and Structural Dynamics,* Vol. 36, pp. 2,227–2,248.

Qu, Z., Wada, A., Motoyui, S., Sakata, H. and Kishiki, S. (2012), "Pin-Supported Walls for Enhancing the Seismic Performance of Building Structures," *Earthquake Engineering and Structural Dynamics,* Vol. 41, No. 14, pp. 2,075–2,091.

Sause, R., Ricles, J.M., Chancellor, N.B. and Roke, D.A. (2014), "Hybrid Simulations of Self-Centering Concentrically-Braced Frames Subject to Extreme Ground Motions," *Proceedings of the 10th US National Conference on Earthquake Engineering,* July, Anchorage, AK, EERI.

Simpson, B.G. and Mahin, S.A. (2016), "Reducing Concentrations of Inelastic Demand with a Strongback," 2016 EERI Graduate Student Paper Competition winner, 12 pages.

Simpson, B. and Mahin, S. (in press), "Experimental and Numerical Study of a Strongback System to Mitigate Weak Story Behavior in Steel Braced Frames," *Journal of Stuctural Engineering.*

Simpson, B.G., Mahin, S.A. and Lai, J.W. (in press), "Cyclic Testing of Older Steel Braced Frames." Report PEER-2017/XX, Pacific Earthquake Engineering Research Center, Berkeley, CA.

Slovenec, D., Sarebanha, A., Pollino, M., Mosqueda, G. and Qu, B. (2017), "Hybrid Testing of the Stiff Rocking Core Seismic Rehabilitation Technique," *Journal of Structural Engineering*, ASCE, Vol. 143, No. 9.

Taga, K., Kato, M., Tokuda, Y., Tsuruta, J. and Wada, A. (2004), "Hints on How to Design Passive Control Structure Whose Damper Efficiency Is Enhanced, and Practicality of This Structure," *Proceedings of the Passive Control Symposium,* Tokyo Institute of Technology, Yokohama, Japan, pp. 105–112.

Takeuchi, T., Chen, X. and Matsui, R. (2015), "Seismic Performance of Controlled Spine Frames with Energy-Dissipating Members," *Journal of Constructional Steel Research*, Vol. 114, pp. 51–65.

Takeuchi, T. and Suzuki, K. (2003), "Performance-Based Design for Truss-Frame Structures Using Energy Dissipating Devices," *Proceedings of the STESSA 2003 Conference,* Naples, Italy, pp. 55–61.

Tremblay, R. (2000), "Influence of Brace Slenderness on the Seismic Response of Concentrically Braced Steel Frames," *Proceedings of the STESSA Conference,* Montreal, Canada, pp. 527–534.

Tremblay, R. (2003), "Achieving a Stable Inelastic Seismic Response for Concentrically Braced Steel Frames," *Engineering Journal,* AISC, Vol. 40, No. 2, pp. 111–129.

Tremblay, R., Ben Ftima, M. and Sabelli, R. (2004), "An Innovative Bracing Configuration for Improved Seismic Response," *Proceedings of Recent Advances and New Trends in Structural Design International Colloquium,* Timisoara, Romania, pp. 419–430.

Tremblay, R., Chen, L. and Tirca, L. (2014), "Enhancing the Seismic Performance of Multi-Storey Buildings with a Modular Tied Braced Frame System with Added Energy Dissipating Devices," *International Journal of High-Rise Buildings,* Vol. 3, No. 1, pp. 21–33.

Tremblay, R. and Merzouq, S. (2004), "Dual Buckling Restrained Braced Steel Frames for Enhanced Seismic Response," *Proceedings of the Passive Control Symposium,* Tokyo Institute of Technology, Yokohama, Japan, pp. 89–104.

Tremblay, R. and Poncet, L. (2004), "Improving the Seismic Stability of Concentrically Braced Steel Frames," *Proceedings of the 2004 SSRC Annual Technical Session & Meeting*, Long Beach, CA, pp. 19–38.

Tremblay, R., Robert, N. and Filiatrault, A. (1997), "Tension-Only Bracing: A Viable Earthquake-Resistant System for Low-Rise Steel Buildings?" *Proceedings of the SDSS '97 Fifth International Colloquium on Stability and Ductility of Steel Structures,* Nagoya, Japan, 2, pp. 1,163–1,170.

Tremblay, R. and Stiemer, S.F. (1994), "Back-up Stiffness for Improving the Stability of Multi-Story Braced Frames under Seismic Loading," *Proceedings of the SSRC Annual Task Group Technical Session,* Bethlehem, PA, pp. 311–325.

Uriz, P. and Mahin, S.A. (2008), "Toward Earthquake Resistant Design of Concentrically Braced Steel-Frame Structures," Report PEER-2008/08, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

Wada, A., Qu, Z., Ito, H., Motoyui, S., Sakata, H. and Kasai, K. (2009), "Seismic Retrofit Using Rocking Walls and Steel Dampers," *ATC/SEI Conference on Improving the Seismic Performance of Existing Buildings and Other Structures*, ASCE, San Francisco, CA.

Wu, D. and Lu, X.L. (2015), "Structural Performance Evaluation of a New Energy-Dissipation and Light-Weight Rocking Frame by Numerical Analysis and Experiment," *Proceedings of the 10th Pacific Conference on Earthquake Engineering,* Sydney, Australia, Paper No. 191.