conference preview

STURDY SPINE

BY BARBARA G. SIMPSON

Developing a design methodology for steel strongback braced frames.

A STRUCTURAL SYSTEM is like the human body.

In seismic regions, inelastic energy dissipation (like brace buckling or beam yielding) is performed by the muscles. The structural skeleton resists gravity and lateral forces through a framework of bones. The rib cage is defined by beams, the space between ribs is represented by building stories and the limbs are characterized by columns.

But the analogy is incomplete. Conventional structural skeletons do not typically include a spine or backbone. While the flexural strength and stiffness of beams and columns can *implicitly* redistribute seismic demands, conventional structures typically do not have an *explicit* mechanism (like a spine) to distribute yielding. If the implicit mechanism is insufficient or unreliable, conventional systems tend to form story mechanisms, concentrating damage in only a few stories during large earthquakes.

Enter strongback braced frames, which modify conventional structural skeletons to include an explicit structural steel spine or "strongback." Like the spine in a human body, the strongback ties the stories of a structure together. Designed to remain essentially elastic during major earthquakes, the strongback is intended to mitigate story mechanisms, redistribute inelastic demands vertically and efficiently mobilize the inelastic components (muscles) across every story.

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While the strongback system has been employed successfully in both research and practice, its dynamic behavior has not been systematically assessed or evaluated. Just as importantly, practical code-oriented design methods have not yet been developed or validated. To develop a comprehensive design method for strongback braced frames, it is important to understand how story mechanisms form, how the strongback behaves, how to estimate strongback demands and how to implement research on the strongback into practice.

Story Mechanisms

Steel braced frames are inherently stiff systems and are naturally efficient in resisting seismic demands. During earthquakes, concentrically braced frames dissipate energy through the post-buckling behavior of the braces. Successful designs recognize and account for the redistribution of forces as braces buckle in compression, yield in tension and subsequently lose strength after buckling.

But reliance on brace buckling can be less than ideal. To attain acceptable behavior, diagonal braces must be specially detailed to exhibit a stable inelastic response. The incorporation of special ductile detailing, the introduction of buckling-restrained braces (BRBs) and the inclusion of capacity-design principles in modern building codes have resulted in improved brace deformability and protection of critical connections and elements.

But while these and other design requirements have improved their reliability and ductility, conventional steel braced frames continue to be susceptible to story mechanisms (see Figure 1). Story mechanisms in braced frames stem from the inelastic behavior of the braces. When a brace in a story buckles, that story becomes relatively weaker than the stories that have remained elastic. Subsequent yielding is then promoted in the weakened story, resulting in a story mechanism. In buckling-restrained brace frames (BRBFs), the low post-yield stiffness of the BRBs promotes concentrations of story drift, resulting in similar behavior.

During an earthquake, multi-story structures can exhibit non-uniform story drift demands, increasing the likelihood of forming a weak or soft story mechanism. These concentrated demands can increase local structural and nonstructural damage, cause earlier member failures and result in significant residual displacements, potentially leading to extensive or impractical repairs following an earthquake.

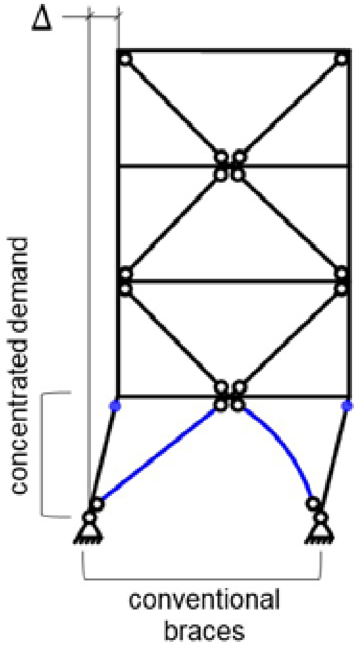
Strongback Characteristics

Story mechanisms arise from a limited ability to redistribute inelastic demands to adjacent stories. The inclusion of an essentially elastic strongback provides an alternative force path to distribute demands to delay or prevent story mechanisms (see Figure 2).

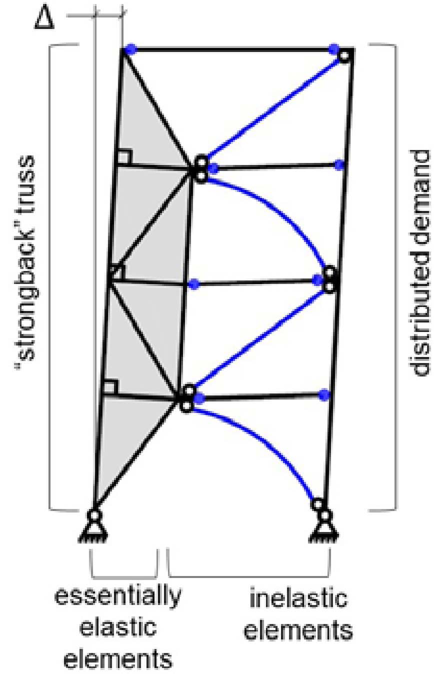
The strongback braced frame is a hybrid of a conventional inelastic system and an essentially elastic steel truss. Braces and beams in the inelastic portion are designed and detailed to yield. Typically, this energy dissipation is performed by conventional buckling braces or BRBs. The opposite strongback truss is then proportioned to remain essentially elastic, resulting in a relatively stiff and strong vertical spine. Axial forces and bending moments developed in these inelastic elements are transferred vertically to adjacent stories through the strongback.

▲ A new four-story laboratory building in Berkeley, Calif., was one of the first major applications of a strongback braced frame using BRBs. By using an asymmetric strongback spine, Tipping Structural Engineers was able to cut the required frames almost in half and the number of BRBs by one-third.

▼ Figure 1. Plastic mechanism for concentrically braced frames.



▼ Figure 2. Plastic mechanism for strongback braced frames.



Gregory P. Luth and Associates, in association with Exponent, took advantage of the flexibility and redundancy of a modified strongback rocking system to economically accommodate significant changes and ill-defined loading conditions for the fast-paced design and construction of the Tesla Gigafactory in Reno, Nev.

The strongback spine is not intended to provide supplemental lateral strength. Rather, the spine pivots about its base to distribute demands in an imposed first mode shape. Inelastic demands are not eliminated but averaged, resulting in reduced peak and residual drifts. Since behavior is no longer controlled by a story mechanism, the integrated hybrid system is stronger and more ductile, increasing safety and reducing the probability of yellow or red tagging following an earthquake.

Estimating Demands

The essentially elastic nature of the strongback spine ensures that yielding occurs primarily in the designated inelastic components. Demands and details in those inelastic regions can be determined by traditional design methods typical of a conventional system—e.g., as required by ASCE/SEI 7-16: *Minimum Design Loads for Buildings and Other Structures*. To remain essentially elastic, strongback elements could then be designed to be stronger than the demands delivered by the expected maximum capacity of the inelastic members (including overstrength, strain hardening, etc.) per capacity-based design.

But traditional capacity design alone is an insufficient lower bound on the demands in the strongback spine. Capacity design assumes that the capacities of the inelastic elements limit the forces that can develop during an earthquake. However, since the strongback elements are dually designed to remain elastic and resist lateral loads, they continue to accumulate demands after the inelastic elements have yielded and as the ground shaking intensifies.

These seismic demands are dynamic and constantly changing with time. Though the displaced shape is dominated by a first mode (inverted triangular) response (refer to Figure 2 again) the demands in the strongback elements are maximized under higher mode (bending) contributions. Thus, the required strength of the essentially elastic components is still bounded by capacity design principles but is additionally bounded by elastic or partially elastic higher mode effects. These demands can be significantly higher than those predicted solely from capacity design methods.

From Research to Practice

The behavior of the strongback is inherently dynamic. While an iterative nonlinear dynamic analysis approach is possible, it is not a design method that would be regularly used by design engineers for most steel building structures. Moreover, an iterative approach still needs a preliminary design to initiate the iterative process. A simplified static method that envelopes the demands from higher modes with the demands from the inelastic components can provide a simple estimate of strongback demands for design.

Though cost studies are still preliminary, both research and practice have suggested that the strongback system can achieve better behavior than a conventional braced frame at comparable initial construction costs. Compared to a conventional braced frame in which all the braces yield, the strongback truss may require larger brace and column sizes to remain elastic. However, the overall number of BRBs can be reduced compared to a traditional BRBF. Moreover, ordinary details can be used in the essentially elastic truss if the strongback is designed by a large enough margin to remain essentially elastic under a rare earthquake.

Costs can additionally be balanced by the strongback's inherent vertical redundancy. Provided the strongback is strong enough to bridge across multiple stories, the spine provides an alternative force path that could be used to circumvent structural irregularities. For instance, one or more of the inelastic braces could be removed to satisfy architectural constraints or to compensate for unanticipated failures in the inelastic elements. Inelastic braces can also be disproportionately sized to their expected demand-to-capacity ratio, allowing the same inelastic brace size to be used in every story.

In research, numerical analyses and one experimental test have demonstrated that strongback braced frames can successfully distribute inelastic demands and mitigate concentrations of damage. In addition, strongback braced frames have been implemented and constructed in practice (more on this in the session; see the two photos). As a simple and robust modification of a conventional braced frame, the strongback braced frame alleviates structural or architectural irregularities and promises potential for an in-between solution between basic seismic performance and enhanced seismic performance objectives. ■

This article is a preview of Session N2 "AISC Research: Development of a Design Methodology for Steel Strongback Braced Frames" at NASCC: The Steel Conference, taking place April 11-13 in Baltimore. Learn more about the conference at ***www.aisc.org/nascc****.*