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Design and Performance Comparison of Strongback Systems and Typical Chevron BRB Frames

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ABSTRACT

Structural engineering is moving towards the design of enhanced performing buildings under earthquake events to improve the resiliency of urban communities. Buckling Restrained Braced Frames (BRBF) have been widely adopted to resist lateral loads. However, typical configurations could be subjected to drift concentration, leading to large story drifts and uneven utilization of the BRBs with building height. Studies have suggested that innovative configurations, such as pivoting or rocking frames, can provide a better distribution of the story drift by delaying or preventing story mechanisms and spreading the energy dissipation to adjacent stories across the building height. These types of bracing configurations utilize as essentially elastic spine, or *strongback*, to induce a global tilting mode. However, since the spine is designed to remain elastic, additional design considerations are needed to size the elements in strongbacks. This study presents a comparative study between traditional chevron BRBF and strongback BRBF systems for a set of buildings with different heights and tributary areas. Results show that the pivoting and rocking strongback result in reduced the peak story drift with more uniform distribution of drift demands. The cost of these alternatives, per frame, was similar to the chevron BRBF.

Introduction

Over the past century, the seismic design of structures has resulted in improved design practices to provide communities with safer buildings against natural hazards. Interactions between researchers, industry, and policy makers have enabled the development of a wide range of structural systems that are continuously adopted and improved with evolving standards and design requirements [1–3]. Although typical Buckling Restrained Brace Frames (BRBF) have been widely used to withstand lateral forces to satisfy code requirements, BRBFs are also prone to drift concentrations over a few stories, leading to larger peak drift demands and an uneven utilization of the structural

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elements with building height [4]. Innovative bracing configurations that employ an essentially elastic spines, herein referred to as *strongbacks* (also referred to as *masts* by others), could provide more uniform drifts and damage distribution across the building height [5,6]. The strongback provides an elastic load path to mitigate concentrations of demands in one or a few stories and to facilitate the spread of energy dissipation to adjacent stories [7]. These systems can be designed to rock (uplift) or pivot about a pinned base. As the strongback is designed to remain elastic, studies have suggested that forces arriving from the contribution of higher modes cannot be neglected. As a result, many authors have proposed ways to include these demands in the strongback's design, including modified versions of response spectrum analysis or static analysis procedures [8–10].

This paper summarizes a generalized workflow that can be used to design a traditional chevron BRBF and highlights additional requirements needed to proportion BRBFs employing strongbacks. A set of chevron and strongback BRBF archetypes, comprised of varied tributary areas and heights, were designed based on the workflow. Their global response was compared in terms of story drifts. Additionally, the cost of the lateral systems was estimated based on the steel tonnage and number of BRBs.

Design workflow

Fig. 1 provides a generalized design workflow to compare the proportioning of elements in: [i] typical chevron BRBF configurations, and [ii] strongback BRBF configurations. The design of the lateral system begins with estimates of the seismic forces. Energy dissipation is provided by BRBs (displacement-controlled). Then, other methods can be used to proportion the remaining elements or actions (force-controlled), which are designed to remain elastic and promote stability. The estimation of demands in force-controlled elements can be carried out using capacity design or plastic analysis, and referenced against the overstrength factors provided for the chosen lateral-force resisting system. However, these approaches might not be enough to establish the forces in systems using strongbacks, particularly due to higher-mode effects, requiring additional considerations for strongback BRBFs.

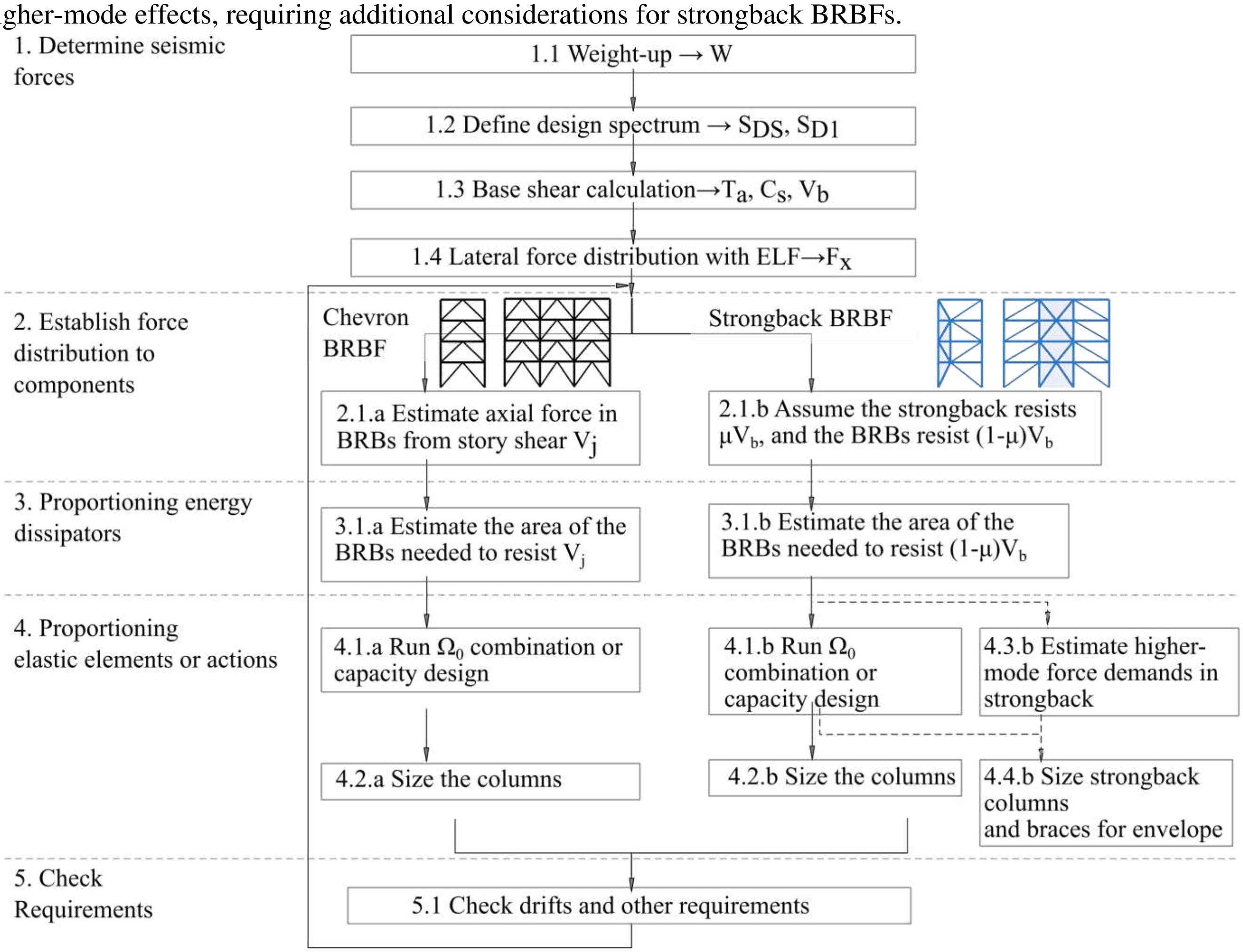

Figure 1. Generalized design workflow for chevron and strongback BRBFs.

To establish the design base shear, a response reduction factor, R, equal to 8 was used for both systems. Initially, the typical Equivalent Lateral Force (ELF) procedure was adopted to estimate the lateral force distribution across the building height based on the design base shear. In the case of the chevron BRBF, the design assumes the BRBs resist the entirety of the story shear in every story. The columns are designed to resist gravity loads and the forces delivered by the BRBs based on their adjusted strength, based using capacity design, and capped by the load combination with overstrength factor, $\Omega_0 = 2.5$. In the strongbacks BRBFs, the story shear is assumed to be shared between the BRBs and elastic braces in the strongback, as defined by the ratio μ. Additional design considerations needed for the strongback to remain elastic include adjustments to account for higher-mode contributions, as shown by the dotted lines. Finally, the workflow ends by checking that the final proportioning satisfies force and drift requirements. Design of the beams is not included in the workflow and would need to be designed for any additional demands resulting from the kinematics of systems using strongbacks.

Application setting

Archetype development

A set of 12 archetypes (6 chevron BRBFs and 6 strongback BRBFs) were designed using the design workflow. The buildings were proportioned with respect to a design response spectrum with $S_{DS} = 1.07$ and $S_{D1} = 0.68$. The redundancy factor and three-dimensional effects were neglected in the design.

The set includes the design of seismic-force resistant systems for buildings of 4, 8 and 16 stories with two different footprints of 27,000 and 54,000 ft^2; see Fig 2. The 16-story buildings are considered only for proof-of-concept due to code height limitations. For the smaller footprint archetypes, one-bay chevron BRBFs were compared to strongback BRBFs with a pivoting strongback embedded in the same bay as the BRBs. For the larger footprint archetypes, three-bay chevron BRBFs were compared to strongback BRBFs with two bays with BRBs sandwiching one bay with a rocking (uplifting) strongback. The 4- and 8-story buildings were assumed to have two lines of frames per each direction of the loading, while the 16-story buildings had four lines of frames per direction.

System response

The archetypes were modeled in PERFORM-3D [11] software package and the response was compared using nonlinear dynamic analysis for a suite of scaled ground motions; see the median of the peak story drift ratios for the ground motions scaled to the design earthquake and MCE intensities in Figure 2. The story drift profile for the chevron BRBF configurations indicate drift concentrations, which are significant for the MCE event. The 4-story chevron BRBFs exhibited drift concentration in the lower stories, while taller buildings exhibited drift concentration in both the lower and upper stories. For the pivoting and rocking strongback BRBFs, the peak drifts profile is more uniform compared to the chevron BRBFs, as the strongback mitigates concentrations of drift. For both considered intensities, peak story drifts of the strongback BRBFs were reduced in stories that tended to concentrate damage in the chevron BRBFs.

Although not shown here, force demands in the elastic elements of the strongback extracted from the nonlinear dynamic analyses corroborated the need to estimate those design forces using non-conventional approaches that better represent the effects of higher modes. If those additional forces are not considered in the design, as is typically neglected for traditional seismic-force resisting systems, the intended elastic elements would likely behave in the inelastic range. More exhaustive analyses are needed with 3D models, collapse analysis, and other strongback configurations to gage relative performance.

Cost in thousands of dollars per frame is also shown for each design solution in Figure 2, considering only the steel tonnage and number of BRBs. The cost assumed \$2.50 per pound of steel and \$10,000 per BRB. The price per frame in a pivoting strongback BRBFs is slightly higher than the chevron BRBFs. For the wider archetypes (larger footprint), the rocking strongback BRBFs have an economic advantage over the three-bay chevron BRBFs. In general, the cost of the Strongback BRBF, per frame, differs ±10% from the cost of a chevron BRBF, but with the added benefit of enhanced structural performance.

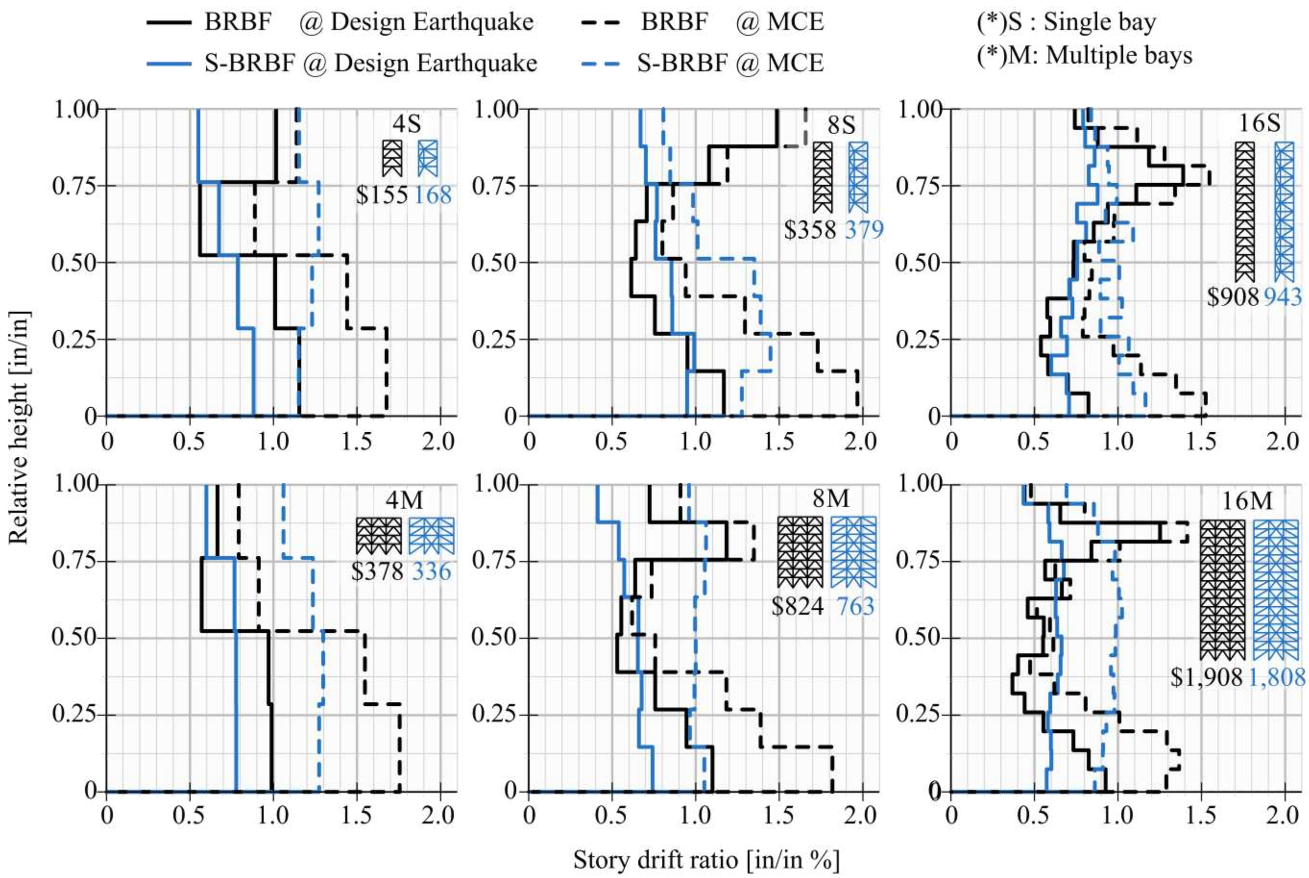

Figure 2. Median story drift ratio under DBE and MCE for all the archetypes, and cost in thousands of dollars of each frame.

Conclusions

Traditional chevron BRBF and alternative strongback BRBF systems were designed with different heights and tributary areas. Differences in their design were illustrated in a generalized design workflow. Observations, limitations, and future work are summarized below:

- The design of elastic elements in the strongback requires additional estimates of the force demands due to higher-mode contributions. Methods available in the literature could be used to approximate those demands as an alternative to iterative non-linear dynamic analysis.
- BRBFs with strongbacks exhibited a more uniform distribution of drift and smaller peak drift demands compared to typical chevron BRBF configurations, which can be correlated to better structural performance.
- The estimated cost of the strongback BRBFs, per frame, variates in ±10% from the cost of a chevron BRBF. Future studies are needed to consider other possible advantages of strongback system, such as relaxing system or detailing requirements and implications on the foundations.
- The current study was limited to the drift response of 2D models. Future studies should consider a more robust assessment of performance at the global and local level, including collapse analysis, evaluation of different means of incorporating higher-mode effects, and quantification of the system seismic performance factors.

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