PRELIMINARY PERFORMANCE ASSESSMENT OF SPECIAL CONCENTRICALLY-BRACED FRAMES FOR MODERATE SEISMIC REGIONS

K. Grabner\textsuperscript{1} and L. Fahnestock\textsuperscript{2}

ABSTRACT

Steel concentrically-braced frames (CBFs) are widely used lateral force resisting systems with high strength, stiffness, and material efficiency. Special concentrically-braced frame (SCBF) systems are a type of CBF commonly used in high seismic regions because they are designed to permit large inelastic drifts. Ductile detailing and capacity design requirements ensure braces are the main source of energy dissipation in the system. While the use of SCBFs in high seismic regions is prevalent, they are not frequently designed when seismic demands are lower. Low-ductility steel CBFs, the typical system used in low to moderate seismic regions, do not have the same detailing or proportioning requirements as SCBFs, which permits lighter system weights at the expense of ductile frame behavior. Structural behavior of low-ductility CBFs relies on reserve capacity, or secondary stiffness and strength, after initial brittle limit states. This study considers SCBFs designed for moderate seismic regions as a direct comparison to recent assessments of frame behavior and economy of widely used low-ductility CBFs, namely the R=3 CBF and the ordinary concentrically-braced frame (OCBF). Numerical models for a suite of three story braced frames are analyzed to characterize system behaviors in regions with moderate seismic demands. Pushover analyses are conducted on the models to study the benefit of inherent system ductility on collapse mitigation, to consider the effect of frame type on system economy, and to evaluate the efficacy of low-ductility CBFs widely used in practice.

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ABSTRACT

Steel concentrically-braced frames (CBFs) are widely used lateral force resisting systems with high strength, stiffness, and material efficiency. Special concentrically-braced frame (SCBF) systems are a type of CBF commonly used in high seismic regions because they are designed to permit large inelastic drifts. Ductile detailing and capacity design requirements ensure braces are the main source of energy dissipation in the system. While the use of SCBFs in high seismic regions is prevalent, they are not frequently designed when seismic demands are lower. Low-ductility steel CBFs, the typical system used in low to moderate seismic regions, do not have the same detailing or proportioning requirements as SCBFs, which permits lighter system weights at the expense of ductile frame behavior. Structural behavior of low-ductility CBFs relies on reserve capacity, or secondary stiffness and strength, after initial brittle limit states. This study considers SCBFs designed for moderate seismic regions as a direct comparison to recent assessments of frame behavior and economy of widely used low-ductility CBFs, namely the R=3 CBF and the ordinary concentrically-braced frame (OCBF). Numerical models for a suite of three story braced frames are analyzed to characterize system behaviors in regions with moderate seismic demands. Pushover analyses are conducted on the models to study the benefit of inherent system ductility on collapse mitigation, to consider the effect of frame type on system economy, and to evaluate the efficacy of low-ductility CBFs widely used in practice.

Introduction and Background

Special concentrically-braced frames (SCBFs) are expected to exhibit ductile frame behavior and inelastic drift capacity due to brace geometric limits, and the member and connection ductile detailing and proportioning required by the AISC Seismic Provisions [1], representing a transparent connection between design objectives and intended behavior. However, where seismic demands are lower, SCBFs are not common since other CBFs with less stringent design requirements, predominantly low-ductility CBFs, are permissible by ASCE 7-10 [2]. These low-ductility CBFs exhibit initial brittle limit states, including weld fracture, and can prevent collapse.

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through system reserve capacity, which is not directly considered in design.

OpenSees numerical models for frame designs of chevron and split-x configurations of each of the three frame types are developed and pushover analyses are performed. The performance of the SCBFs is compared to that of the low-ductility CBFs, the R=3 CBF and the OCBF. In the context of recent research on low ductility CBFs which identified and quantified the potential sources of reserve capacity [3], this study of the behavior of SCBFs in low to moderate seismic regions investigates the influence of intentional system ductility on the performance of CBFs.

**System Design**

The prototype building in this study is a three-story structural steel building located in Boston, MA. The lateral force resisting system is designed to have two CBFs in each direction. The suite of CBF designs consists of: chevron and split-x SCBFs (R=6), chevron and split-x OCBFs (R=3.25), and chevron and split-x R=3 CBFs.

The motivation to design both chevron and split-x frames is to assess the influence of brace configuration on the proportion of demand supplied to the beams and columns. The resultant force of the tension and compression braces on the beam midpoint in a chevron can be large at brace capacities, and this force can lead to large beam sizes in the SCBF chevron configuration [4], while split-x configurations have braces on either side of the beam to balance demands. SCBF designs further differ from low-ductility CBFs with capacity design and ductility requirements for connections, beams and columns. The member sizes for the system designs are summarized in Table 1.

**Table 1. Summary of member sizes for braced frame system designs.**

<table>
<thead>
<tr>
<th>Frame Designation</th>
<th>Story 1 Braces HSS ASTM 1085</th>
<th>Story 2 Braces HSS ASTM 1085</th>
<th>Story 3 Braces HSS ASTM 1085</th>
<th>Level 2 Beam</th>
<th>Level 3 Beam</th>
<th>Roof Beam</th>
<th>Columns</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCBF Chevron</td>
<td>5(\frac{3}{5})x5(\frac{3}{5})x3/8</td>
<td>5(\frac{5}{6})x5(\frac{5}{6})x3/8</td>
<td>4x4x1/4</td>
<td>W36x170</td>
<td>W36x150</td>
<td>W30x108</td>
<td>W14x68</td>
</tr>
<tr>
<td>SCBF Split-X</td>
<td>5(\frac{5}{6})x5(\frac{5}{6})x3/8</td>
<td>5(\frac{5}{6})x5(\frac{5}{6})x3/8</td>
<td>4x4x1/4</td>
<td>W24x84</td>
<td>W18x55</td>
<td>W30x108</td>
<td>W14x68</td>
</tr>
<tr>
<td>OCBF Chevron</td>
<td>8x8x1/2</td>
<td>8x8x1/2</td>
<td>8x8x1/2</td>
<td>W40x167</td>
<td>W36x135</td>
<td>W21x62</td>
<td>W12x65</td>
</tr>
<tr>
<td>OCBF Split-X</td>
<td>7x7x1/2</td>
<td>7x7x1/2</td>
<td>8x8x1/2</td>
<td>W12x26</td>
<td>W12x26</td>
<td>W12x26</td>
<td>W12x65</td>
</tr>
<tr>
<td>R=3 Chevron</td>
<td>9(\times)9x1/4</td>
<td>8x8x1/4</td>
<td>6x6x1/4</td>
<td>W12x26</td>
<td>W12x26</td>
<td>W12x26</td>
<td>W12x53</td>
</tr>
<tr>
<td>R=3 Split-X</td>
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<td>8x8x1/4</td>
<td>6x6x1/4</td>
<td>W12x26</td>
<td>W12x26</td>
<td>W12x26</td>
<td>W12x53</td>
</tr>
</tbody>
</table>

**Numerical OpenSees Model**

Since there are two braced frames in each direction, half of the prototype building is modeled in 2-D to simplify analysis, including the braced frame and adjacent gravity bays with gravity load to consider geometric effects. The gravity columns are modeled with elastic stiffness and beam-to-column connections to include their contribution to the system. The braces are modeled using distributed plasticity displacement-based elements (DBEs) with a sine sweep initial imperfection of L/1000. Beams and columns are modeled with concentrated plasticity Ibarra-Medina-Krawinkler (IMK) nonlinear springs. The gusset plate regions are modeled with rotational stiffness at the ends of the braces and rigid sections in the beams and columns. The low ductility frames include the possibility of weld fracture throughout the analyses.
Results and Discussion

The pushover curves generated from analyses of the six braced frame designs are differentiated by brace configuration and shown in Figure 1. The design base shear of each frame is shown as a dotted line in the figure. At low levels of roof drift, the R=3 and OCBFs exhibit brittle limit states, seen as sharp drops in capacity, while the SCBF exhibits higher capacity at large drifts.

Figure 1. Pushover analysis results for the SCBF, OCBF, and R=3 CBFs.

Figure 2 shows the demand-to-capacity ratios (DCR) versus roof drift for the beams at each story. The relationship demonstrates the distribution of demand amongst the members in each story as drift increases. Figure 3 shows the brace axial force versus axial deformation, which demonstrates the ductility localized in each brace at the different stories in each frame.

Figure 2. Demand-to-capacity ratio of beams in the braced bay versus roof drift.
In general, SCBFs demonstrate the ability to sustain large force levels across members in different stories as the demand shifts throughout the pushover analysis, while the low-ductility frames are limited by the brittle behavior seen in weld fracture and the effective loss of a brace to the capacity of the system. The demand in the columns of the low-ductility CBFs consistently concentrates in the first story where shear is high, which can perpetuate the brittle mechanisms observed, while the response of the SCBF is not necessarily driven by the first story behavior.

Conclusions

Special concentrically-braced frames contrast low-ductility braced frames in their ability to display ductile frame behavior as a result of their intentional analysis and design requirements for ductility. This preliminary pushover analysis assessment of three-story SCBFs establishes a benchmark to compare to the frame behavior of similar low ductility CBFs.

References