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Cyclic testing and performance evaluation of buckling-restrained knee-braced frames

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ABSTRACT

This paper presents the behavior and design concept of an efficient structural steel system based on the applications of buckling-restrained knee braces (BRKBs). The advantages of a buckling-restrained knee-braced frame (BRKBF) include relatively simple connections, reparability after an earthquake, and fewer obstructions than conventional bracing systems. Various BRKBF configurations can be designed and detailed for different levels of strength, stiffness, and ductility. BRKBFs are designed so that all inelastic activities are confined to the BRKB. The key design concepts for ensuring the ductile behaviors of BRKBFs are first summarized. Cyclic tests of large-scale BRKBF sub-assemblage specimens are then carried out. The results from both experimental and analytical studies of the behavior of BRKBFs show that they can be a viable alternative to conventional structural systems.

1. Introduction

Knee braces were widely used in the past for wind-resistant design. The advantages of knee braces were realized in the early days of high-rise building design [1]. Knee braces can be used in exterior frames and still allow a large percentage of the building face to be completely clear of obstruction. When used in interior frames, the restrictions on the areas and the sizes of doors and passageways are also minimized. Despite their architectural advantages, the application of knee braces to seismically resistant structures is still limited. As the current seismic design philosophy places higher emphasis on resiliency, damage control, and structural reparability, improvements in the knee bracing concept for seismic applications have been explored by several researchers [2–6]. Recent developments include the use of buckling restrained knee braces (BRKBs) and BRKBs with truss moment frames [7–12]. BRKBs offer advantages such as enhanced ductility and reparability after an earthquake.

In this research, the seismic behavior and design of a seismically resistant frame utilizing BRKBs are investigated experimentally and analytically. This system, called a buckling-restrained knee-braced frame (BRKBF), is illustrated in Fig. 1. The system is designed so that the BRKBs will yield while the beams and columns remain fully elastic. Through this concept, inelastic activities are confined to the BRKBs only. The BRKBs are expected to enhance the ductility and robustness of the structure due to their stable hysteresis behavior. The beams are connected to the columns using single plate shear connections (SPSCs). SPSCs are simple shear connections that increase the ease of construction and reparability after an earthquake. The key design concepts for the design of BRKBF systems are summarized first. The design of BRKBF in this study is based on a displacement-based procedure which uses pre-selected target drift and yield mechanism as key performance limit states. The results from cyclic tests of large-scale BRKBF sub-assemblages are presented and discussed. Finally, an example of the dynamic response of the proposed system is provided.

2. BRKBF design concept

Based on past experimental and analytical studies of different knee-braced systems [4,5,9–12], the ductile behavior of a KBF appears to hinge on two important design considerations: controlling the knee brace deformation and designing the columns and beams to resist the forces induced by the knee braces. The following sections elaborate upon these two key aspects.

2.1. Knee brace design

For the system shown in Fig. 1, knee braces are the primary designated yielding elements. Hence, they are expected to deform well into the inelastic range. For this reason, BRKBs are more suitable than conventional knee braces. For short BRKBs, the deformation capacity is generally smaller than those of BRBs in a conventional brace frame because the deformation is distributed only over a short length. Therefore, one of the most important aspects in the design of a BRKBF is to ensure that the deformation or strain demand can be safely accommodated by the BRKBs.

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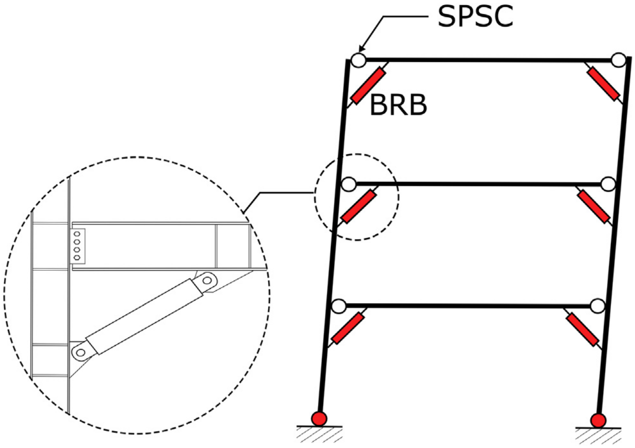

Fig. 1. Buckling restrained knee-braced frame.

In a BRKBF, the size and brace angle must be chosen to balance the function, frame strength, deformation demand, and brace ductility. For the frame in Fig. 2, the strain demands can be estimated from the frame kinematics. As a first approximation, the equation for the BRKB core strain (ε_b) can be developed assuming a rigid beam and column and assuming that the deformation occurs only in the core:

$$\varepsilon_b = \frac{\Delta \sin(2\varphi)}{2H(L_c/L_o)} \tag{1}$$

where Δ is the sway, φ is the angle of the brace with the beam, L_o is the overall brace length, L_c is the length of the yielding core, and H is the story height or the height of the frame. For a frame with an elastic beam and column, the above equation would be true only under plastic conditions (plastic strain versus plastic drift) after the mechanism has formed. Fig. 2 also shows the brace strain demands as a function of the knee brace angle (φ) for different drift angles (Δ/H) for the case of a core length ratio (L_c/L_o) of 0.70. Based on Fig. 2, the strain varies depending primarily on the brace angle and becomes largest for $\varphi = 45°$. For a larger angle, the brace demand decreases. However, as the brace angle becomes larger, the horizontal component of the BRB force decreases, leading to a smaller overall lateral frame strength. Hence, BRKBs with a higher axial strength are required. This may affect the gusset plates and the column sizes, as they have to be designed to accommodate a larger force. Longer braces may also obstruct the passage in the bay. For a smaller angle, the length of the BRKB decreases. This may affect the BRKB deformation capacity because the deformation can be distributed only over a short length. The optimum angle thus depends on the required strength and deformation characteristics of the BRKBs being considered. Based on Fig. 2, the type of brace and brace angle can be chosen according to the expected level of frame drift and the available brace deformation capacity.

As is evident from Fig. 2, one of the most important design considerations is controlling the knee brace deformation. For this reason, a BRKBF is most suited for a displacement-based design procedure. For a given brace angle, a plot such as Fig. 2 can facilitate the selection of the frame target drift. Once the target drift is chosen, a displacement-based design method can be used to obtain the required frame strength to ensure that the drift remains within the target. Any displacement-based design procedures can be used for this purpose. One displacement-based design method that has been successfully used by the authors to design systems with knee bracing is called the performance-based plastic design (PBPD) method [13,14].

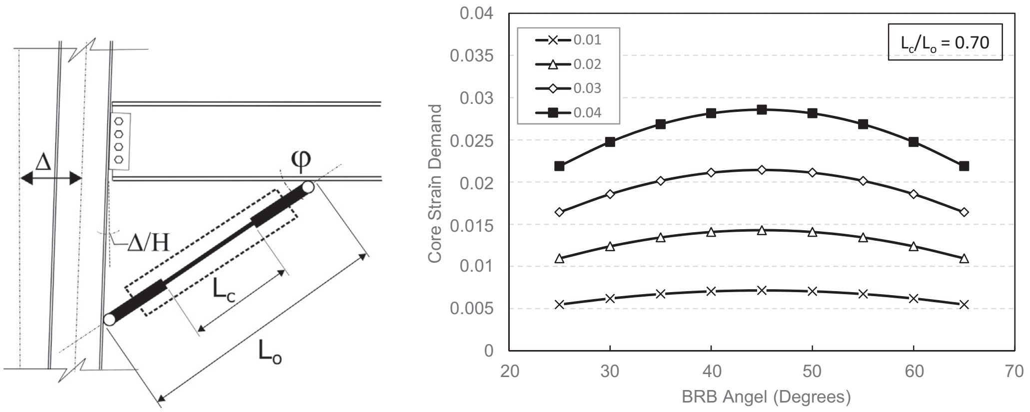

Fig. 2. Deformation of the BRKBs for different drift angles.

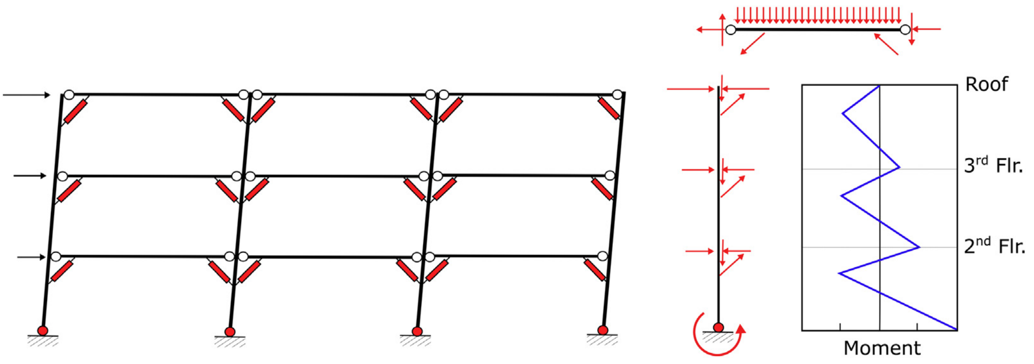

Fig. 3. Column and beam design based on capacity design concept or pushover analysis.