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Buckling-restrained braced frame connection performance

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ABSTRACT

Large-scale experimental studies of buckling-restrained braced frames (BRBFs) have shown that although they display good overall seismic performance, they may have limitations due to connection failure modes that do not allow the braces to realize their full ductility capacity. These experimental results motivate further investigation of BRBF connection behavior. In this study, nonlinear finite element models are used to study BRBF beam–column–brace connections. The models focus on a one-story subassembly extracted from a previously-tested, four-story BRBF. After the baseline finite element analysis results are verified with experimental data, parametric studies varying the connection configuration are used to assess the key factors influencing performance. Connection configuration is shown to have a significant impact on global system response and localized connection demands.

1. Introduction

1.1. Background

Buckling-restrained braced frames (BRBFs), which are concentrically braced frames (CBFs) with buckling-restrained braces (BRBs), provide significantly better seismic performance than conventional steel CBFs. The superior performance of BRBFs results from the robust cyclic performance exhibited by BRBs. Whereas conventional steel braces yield in tension but buckle in compression, leading to sudden strength and stiffness degradation, BRBs yield in tension and compression and develop significant energy dissipation capacity and ductility. These favorable attributes have prompted rapid implementation of BRBFs in the western United States in regions of high seismicity. Fig. 1 illustrates a typical BRB configuration. Numerous isolated tests of BRBs have demonstrated the favorable cyclic characteristics described above and have supported the quick adoption of BRBFs into US design provisions [1,2]. Table 1 shows a sample of ductility demands imposed on BRB test specimens, where maximum ductility demand $\mu_{\max}$ is the maximum deformation normalized by the yield deformation and cumulative plastic ductility demand μ_c is the cumulative plastic deformation normalized by the yield deformation. Table 2 shows a summary of story drift θ_{story} and BRB ductility demands that were obtained from nonlinear dynamic analysis of prototype BRBFs subjected to suites of earthquake ground motions scaled to the design basis earthquake (DBE) and maximum considered earthquake (MCE) hazard levels [2]. These results suggest that BRBs are capable of sustaining the demands that are expected under major seismic events, assuming that BRBs in frame systems will perform in the same way as the isolated BRBs that have been tested.

Several recent large-scale experimental studies of BRBFs have shown that although they display good overall performance, limitations exist due to undesirable connection failure modes. The standardized BRB qualification testing protocol [1] attempts to replicate the demands that would be imposed on a BRB in a frame system, but it has become evident that realistic frame conditions lead to BRB demands that have not been fully represented in qualification tests. Results from large-scale experimental studies of BRBFs provide the best insight into system performance since they more realistically represent interaction between the various frame elements (e.g., BRBs, beams, columns and connections). Results from the research programs summarized below, which studied BRBF system performance, motivate further investigation of BRBF connection behavior.

1.2. Relevant prior research

Aiken et al. [7] conducted cyclic tests on a 0.7-scale one-bay one-story BRBF with full-penetration welded beam–column connections and bolted brace–gusset connections, similar to the details shown in Fig. 2(a). This beam connection configuration is referred to as a moment-resisting connection or continuous beam. In Test 1, the columns yielded in flexure and shear and the gusset plates and beams yielded at the beam–column–brace connections. In Test 2, similar response was observed and cracks formed in a column–gusset weld in a beam–column–brace connection at a story drift less than 0.02 rad. The cracks propagated at story drifts

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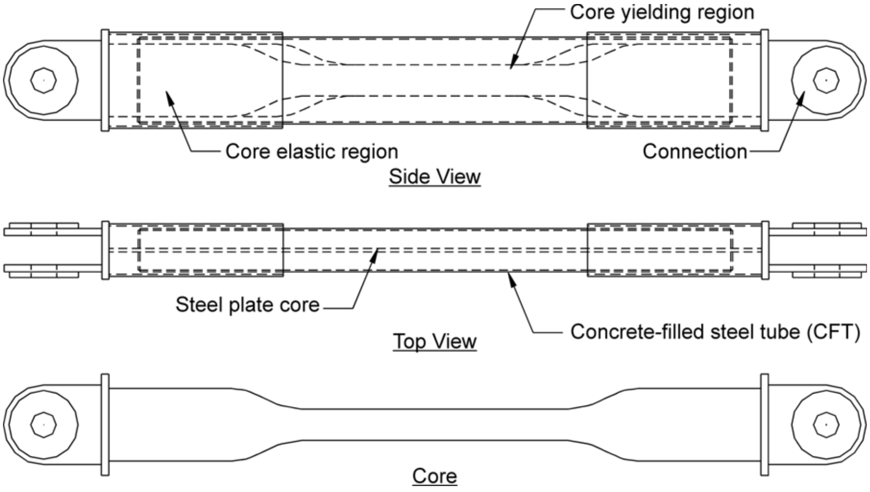

Fig. 1. Typical BRB configuration.

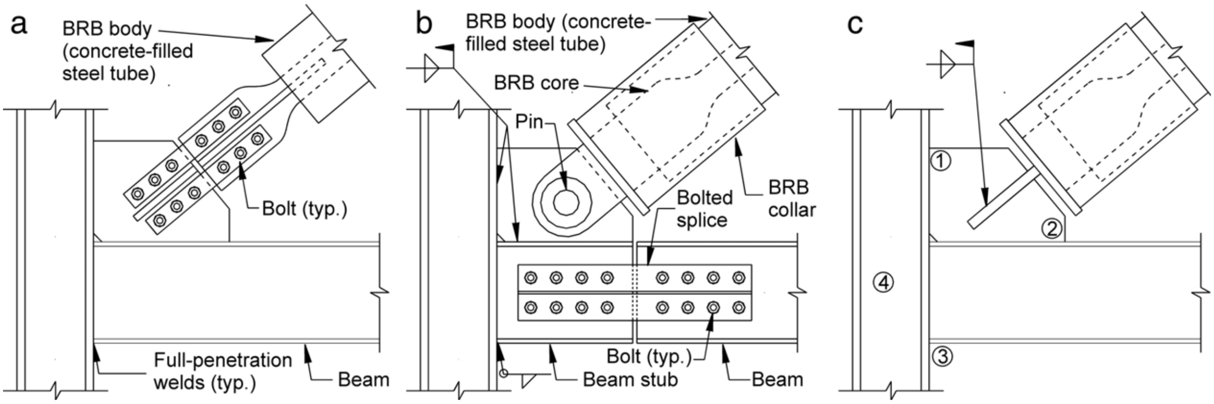

Fig. 2. BRBF connection details: (a) continuous beam, bolted brace; (b) spliced beam, pinned brace; (c) continuous beam, welded brace.

Table 1
Experimental BRB ductility demands.

Reference	Specimen	$\mu_{\max}$	μ_c
Black et al. [3]	99-1	20	324
	99-2	10	879
	99-3	10	279
	00-11	15	1045
	00-12	15	538
Merritt et al. [4]	1	15	900
	2	15	600
	3	10	1600
	4	15	1100
	5	15	1300
	6	15	800
	7	10	1000
	8	10	1000

greater than 0.02 rad and gusset plate distortion was observed. Before Test 3, new gusset plates were installed and stiffener plates were welded at the free edges of the gusset plates adjacent to the columns. During Test 3 at a story drift less than 0.02 rad, a crack initiated at a beam–column–brace connection in the weld between the beam bottom flange and the column. In the first excursion to a story drift of 0.026 rad, a crack developed in the beam bottom flange at the end of the gusset plate in a beam–column–brace connection and propagated through the flange and into the web. This fracture led to beam torsional rotations and BRB out-of-plane displacement and subsequently the strength degraded severely.

Tsai et al. [8] tested a full-scale three-story three-bay dual system, which combined a BRBF with a moment-resisting frame (MRF), using hybrid pseudo-dynamic earthquake simulations. In the BRBF portion of the system, the brace–gusset connections were bolted and bolted web splices were used to connect the beams to beam stubs that were welded to the columns. In Phase 1, out-of-plane gusset plate distortion was observed at various locations in the frame during several tests. Gusset plate stiffeners and lateral braces were added in an attempt to prevent this behavior. Phase

Table 2
Demands from nonlinear dynamic analysis.

Model	Seismic hazard	Response	θ_{story}	$\mu_{\max}$	μ_c
BRBF-6vb2 [5]	DBE	Mean	0.016	10.7	83
		Mean + one standard deviation	0.022	14.5	135
	MCE	Mean	0.045	17.4	139
		Mean + one standard deviation	0.066	25.1	185
BRBF-4 [6]	DBE	Mean	0.020	11.1	70
		Mean + one standard deviation	0.025	14.0	90
	MCE	Mean	0.033	18.4	179
		Mean + one standard deviation	0.041	22.7	391