Journal of Constructional Steel Research 113 (2015) 101–114

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Near-collapse behavior of steel buildings with non-ductile concentrically braced frames

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ARTICLE INFO

Article history:
Received 14 February 2015
Received in revised form 8 June 2015
Accepted 12 June 2015
Available online 19 June 2015

Keywords:
Gravity frames
Concrete slab participation
Non-ductile concentrically braced frame
Seismic collapse analysis

ABSTRACT

Inherent resistance to collapse has been observed in steel buildings with non-ductile concentrically braced frames (CBFs) during past major earthquakes. Understanding of the fundamental characteristics of near-collapse behavior of such buildings will help reveal seismic performance of non-ductile steel structures in existing buildings across the US, and lead to an efficient seismic retrofit of those in seismic zones. This paper presents a seismic evaluation of typical steel buildings using non-ductile CBFs as lateral load resisting structures with focus on their near-collapse behavior, based on the incremental dynamic analysis. The buildings with non-ductile CBFs were found to be fully operational up to 0.5% story drift ratio response with or without gravity frames participating in lateral-load-resisting system. However, the life safety and collapse prevention of the buildings were significantly improved by actually participating lateral-load-resisting systems including CBFs, steel gravity frames and concrete slabs. Furthermore, the post-damage response of the building was more significantly influenced by gravity frames as the damages progressed from its first brace fracture to near collapse, and the participation of the gravity frames had much more impact on the near collapse behavior of a taller building than that of a low-rise building.

1. Introduction

Concentrically braced frames (CBFs) are extensively used as the most popular lateral force resisting (LFR) system for steel buildings in various regions in the US, many of which were designed for wind load, particularly those in older steel buildings and those located in the Central and Eastern United States. Such CBFs are considered non-ductile structures because they were not typically detailed to tolerate much of inelastic deformation either due to brace buckling in compression, or yielding in tension. While seismic performance and design of ductile CBFs for new buildings are extensively studied, concern has been raised about the earthquake hazard in the existing buildings with non-ductile CBFs as LFR structures because of their brittle nature. Although it is convenient to consider a building to be in collapse status as soon as any fracture occurs in its LFR structures during a design process, the actual performance of steel buildings does not seem to be as simple. Lateral and gravity load carrying systems in modern steel buildings are designed exclusively for lateral and gravity loads, respectively, but considerable lateral strength in the gravity-load carrying structures remain when the building is near its collapse. In particular, when a non-ductile CBF system is used in a building, the non-LFR portion of the building structure, such as steel gravity frames and floor system, would inevitably affect seismic performance of the building as a whole, especially at near-collapse response. Understanding the near-collapse behavior of non-ductile building system with brittle CBFs might have practical impact on improving new design of similar buildings and retrofit of existing ones.

Inelastic behavior of non-ductile CBFs subjected to earthquake ground motions has been rarely studied, and little is known about near-collapse phenomena of the buildings with such CBFs as LFR structures. A major challenge in studying the near-collapse response of such structure is the lack of realistic cyclic models describing critical components such as post-fractured braced frames and interaction between steel gravity frame and floor system. Hines et al. [1] presented a study on collapse performance of low-ductility chevron braced steel frames in moderate seismic regions, following a typical procedure traditionally used for buildings with seismic-force-resisting frames. The study included the gravity frames in seismic analysis, but the modeling details are not presented. Recent work by Shen et al. [2] and Wen et al. [3,4] found that near-collapse behavior appeared to be sensitive to structural models used in dynamic analysis, and developed detailed mathematical models of gravity frames considering the interaction between steel frame and concrete floor, and demonstrated that the models are able to simulate experimental results of inelastic behavior of gravity frames in typical steel buildings.

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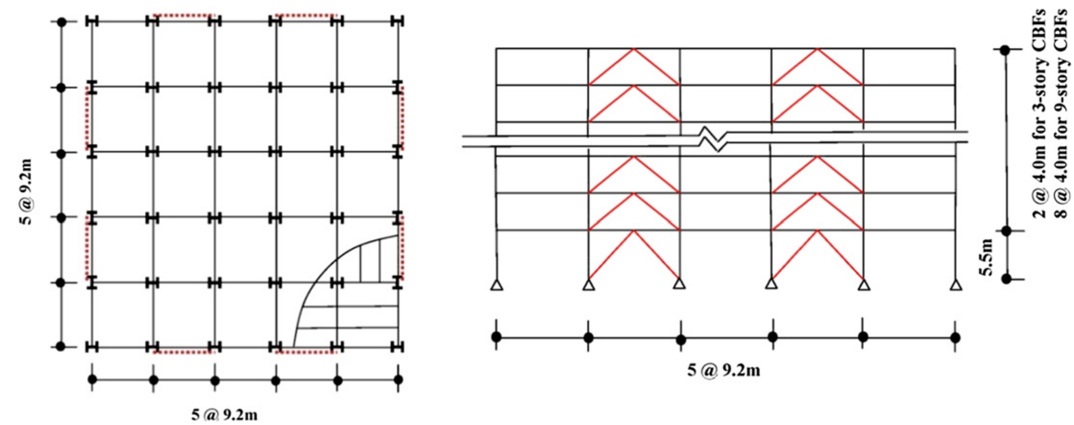
http://dx.doi.org/10.1016/j.jcsr.2015.06.002
0143-974X/



(a) Building floor plan (b) Elevation view on braced bay

Fig. 1. Floor plan and elevation of the building with CBFs.

The goal of this paper is to reveal near-collapse of steel buildings with non-ductile CBFs and conventional gravity frames together with floor system by conducting incremental dynamic analysis. Realistic analytical models of non-ductile CBFs and gravity frames under cyclic loads were employed in two steel buildings with three and nine stories. Incremental dynamic analysis (IDA) was conducted with focus on near-collapse behavior.

2. Structural models

2.1. Buildings with typical non-ductile CBFs

Two multilevel office buildings, as shown in Fig. 1, a low three-story (13.5 m high) and a medium nine-story (37.5 m high), were designed with non-ductile steel CBF (R = 3.25 per ASCE 7 [5]). The buildings were assumed at a low or moderate seismic area, where S_S is 27% g and S_1 is 7% g. Seismic design category (SDC) of these two buildings was defined as SDC C. Dead and live loads of 3.83 kN/m^2 and 2.40 kN/m^2, respectively, were used in the design. The seismic response coefficient, C_s, for three-story and nine-story buildings is 0.093 and 0.050, respectively. The design base shears for these buildings are 3630 kN and 5850 kN, respectively. The sizes were selected based on AISC 341 [6].

The building has symmetric plan dimensions of 46.0 m × 46.0 m, with a story height of 4.0 m for typical floors, 5.5 m for the first floor, and consists of five-bay frames in two orthogonal directions, respectively, spaced at 9.2 m. Two braced bays are arranged on the perimeter, shown in Fig. 1(a). The structural models were intended to consider the building system consisting of LFR, gravity load carrying and floor diaphragm action by two-dimensional models. The columns are assumed to be pinned at the ground. All the connections of brace to column, brace to girder and girder to column are idealized as pin–pin connections.

Each braced frame takes 1/4 total lateral seismic forces. The beams and columns are steel wide-flange sections with specified yielding strength F_y = 345 MPa, and the braces are square hollow structural sections (HSS) with specified yielding strength, F_y = 317 MPa. The final member sizes are summarized in Table 1. The details of connection types in Table 1 will be discussed later in the paper.

Brace-to-girder and brace-to-girder/column connections were designed based on AISC 341 and AISC 360–10 [7] provisions for non-ductile brace connections. Fig. 2(a) shows one typical bracing connection between HSS braces and beam/column connections.

Table 1
Structural member sizes in CBFs.

Story	Braced columns	Braces	Gusset type*	Gravity columns		Beams	
				Corner	Other	Braced bay	All other
Three-story CBF							
3	W12 × 40	HSS6 × 6 × 1/4	1A	W12 × 40	W12 × 40	W21 × 101	W21 × 44
2	W12 × 40	HSS7 × 7 × 1/4	1B	W12 × 40	W12 × 40	W21 × 101	
1	W12 × 53	HSS8 × 8 × 1/4	6	W12 × 53	W12 × 53	W21 × 122	
Nine-story CBF							
9	W12 × 40	HSS6 × 6 × 1/4	1A	W12 × 40	W12 × 50	W21 × 101	W21 × 44
8	W12 × 40	HSS6 × 6 × 1/4	1A	W12 × 40	W12 × 50	W21 × 101	
7	W12 × 40	HSS7 × 7 × 1/4	1B	W12 × 40	W12 × 50	W21 × 101	
6	W12 × 72	HSS7 × 7 × 1/4	3A	W12 × 40	W12 × 72	W21 × 101	
5	W12 × 72	HSS8 × 8 × 1/4	3B	W12 × 40	W12 × 72	W21 × 122	
4	W12 × 87	HSS8 × 8 × 1/4	4	W12 × 45	W12 × 87	W21 × 122	
3	W12 × 87	HSS8 × 8 × 1/4	4	W12 × 45	W12 × 87	W21 × 122	
2	W12 × 152	HSS8 × 8 × 1/4	5	W12 × 72	W12 × 136	W21 × 132	
1	W12 × 152	HSS9 × 9 × 5/16	8	W12 × 72	W12 × 136	W21 × 201	

* Gusset types will be discussed later in the paper.