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Horizontal seismic force demands on nonstructural components in low-rise steel building frames with tension-only braces

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ABSTRACT

Steel building frames consisting of tension-only braces have been recently recognized as adequate lateral force resisting systems for use in low-rise buildings in the regions with seismicity. To further promote the use of such systems, this investigation was focused on developing recommendations for calculating the horizontal seismic force demands on the nonstructural components attached to the systems. Specifically, two full-scale three-story experimental models were designed, constructed and tested using shake tables. The two experimental models differed from each other primarily in that one model consisted of the exterior walls with non-negligible contributions to the system lateral stiffness while the other experimental model did not have such exterior walls. A series of shake table tests using the excitations scaled to different intensity levels were performed on each experimental model. It was found that the existing design and analysis methods appear inadequate in predicting the horizontal seismic force demands on the nonstructural components. Based on the test results, a practical model which can well capture the central tendency of the test results and can be integrated into the existing design method was developed. Test results also revealed that the exterior walls with non-negligible contributions to the system lateral stiffness can arouse larger horizontal seismic force demands on the nonstructural components.

1. Introduction

Steel Concentrically Braced Frames (CBFs) are important seismic force resisting systems that have been widely used all over the world. The conventional steel CBFs consist of the brace members made of the standard steel structural shapes such as channels, angles, tees, wide-flange members and hollow structural shapes that are expected to yield under tension and buckle under compression. The lateral stiffness and resistance of steel CBFs are primarily provided by the brace members. Steel CBFs have recently seen a substantial increase in use, particularly after the 1994 Northridge Earthquake and the 1995 Hyogoken-Nanbu (Kobe) Earthquake [1–6].

Nevertheless, some obstacles still exist, limiting the widespread acceptance of steel CBFs in the design community. Specifically, the brace members, when buckled, develop plastic hinges. Although the existing design documents such as ANSI/AISC 341 [7] and CSA S16 [8] intend to ensure sufficient brace ductility through limiting brace geometries, inelastic rotation of the plastic hinges can cause significant plastic strain concentrations over the plastic region and consequently lead to brace rupture failures under the severe earthquake loading. Moreover, although adoption of the standard structural shapes helps achieve fast designs through the use of the design aids provided in many design documents, strength and stiffness of standard structural shapes cannot be conveniently adjusted based on the design demands, resulting in design inconveniences in some cases. For example, the required cross-section area of a brace member in a CBF can be significantly lower than these of the available standard structural shapes (particularly in design of the low-rise CBFs in which seismic forces are relatively low). Adoption of a brace member with the cross-section area larger than required, although helps increase strength and stiffness of the system, imposes larger seismic demands on the frame members of the CBF according to the capacity design principle, inevitably resulting in less economical designs [9–11].

To alleviate the abovementioned issues, a new CBF system was recently proposed in Japan and China [12,13]. The new CBF system consists of cold-formed Steel Square Tube (SST) columns, wide-flange beams and slender brace members with improved rupture resistances and negligible compressive strengths (which are made of steel plates and referred to herein as the *tension-only* braces). Additionally, unlike the conventional CBFs in which the columns are continuous and the

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beams are discontinuous at the beam-to-column connections, the columns are discontinuous and support the continuous beams at the beam-to-column connections in the new CBF system. While the discontinuous columns do not seem to be consistent with the strong-column-weak-beam philosophy, this design strategy offers the ease of fast prefabrication and erection. More importantly, recent cyclic tests on a full-scale two-story experimental model revealed that such a system can exhibit stable hysteretic behavior up to 10% inter-story drift, making it a potential candidate for low-rise buildings in the regions with seismicity [12,13]. In spite of that, research on seismic design of the nonstructural components in the new CBF system is limited. As will be discussed in detail Section 2, the tension-only braces used in the system have negligible compressive strengths and provide resistances and absorb hysteretic energy primarily only in the tension loading cycles [14,15]. As a result, the new CBF systems exhibit extremely pinched hysteretic behaviors and very limited hysteretic energy absorption capacity. Given that such severely pinched hysteretic behavior and limited hysteretic energy absorption capacity are uncommon in typical lateral force resisting systems (including the conventional CBFs) and that the current design provisions for nonstructural components were developed based on the floor motion data of instrumented buildings consisting of the lateral force resisting systems having quite different hysteretic behaviors from the new CBF systems, there is a research need to evaluate whether or not the current design guidelines for nonstructural components remain applicable for the new CBF systems.

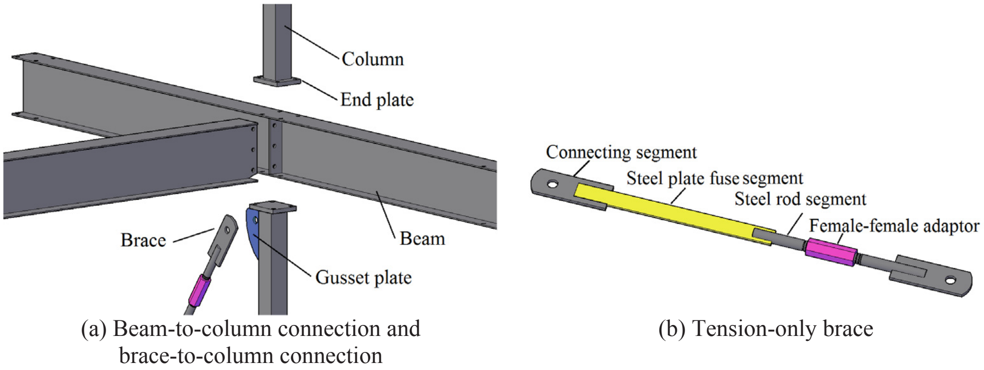
The objective of this research was to experimentally address the issues related to horizontal seismic force demands on the nonstructural components installed in the new CBF systems. Specifically, two full-scale three-story experimental building models were developed and tested using shake tables. The two models represent the systems with and without the exterior walls having considerable contributions to system lateral stiffness, respectively. To achieve the response of the building models under a wide range of ground motions, excitations and their intensities were varied during the shake table tests. The floor motion histories extracted from the experimental models were used to evaluate the existing design models for nonstructural components. The test results presented in this investigation form a basis to better understand the seismic demands on the nonstructural components installed in the new CBFs and help promote implementations of the system in future low-rise building constructions. The following sections first describe the tension-only brace and the new CBF system followed by a brief review of current design models for determination of horizontal seismic force demands on nonstructural components. Next, design and fabrication of the experimental models, test setup, loading program and instrumentation, general observations, and test results and discussions are presented.

2. Tension-only braces and the new CBF system

Fig. 1 illustrates the beam-to-column connection, the brace-to-column connection and the tension-only brace in the new CBF building. As shown in Fig. 1a, the SST columns are connected to the continuous beams through the end plates using high-strength bolts; the braces are connected to the columns through the gusset plates and high-strength bolts. As shown in Fig. 1b, the tension-only brace includes the following segments: the *connecting segments* at the ends through which the brace is bolted to the gusset plates; the *steel plate fuse segment* which yields under tension and buckles under compression; and the two *steel rod segments* which are threaded and connected through a female-female adaptor. The two steel rod segments should be designed using the capacity design approach so that they will remain elastic when the steel plate fuse segment yields under tension. The thin cross-section profiles of the steel plate fuse segments help reduce the strain concentrations due to brace buckling, resulting in higher rupture resistances in the tension-only braces compared with the relatively stocky braces made of the other typical standard structural shapes. Note that a tension-only brace may be stretched into the inelastic range during a strong earthquake event, resulting in relaxation of the brace. The influence of brace permanent elongation can be eliminated through fastening the female-female adaptor that connects the two steel rod segments, improving preparedness of the system for the aftershocks and the following major earthquakes. Further details about the tension-only braces and the new CBF system including the design approach and hysteretic behavior can be found elsewhere [12,13].

3. Existing design methods for nonstructural components

Extensive research efforts have been devoted in the past four decades to improve seismic design of nonstructural components in building structures. Many design methods have been proposed, some of them with a strong empirical base and others based on rigorous principles of structural dynamics. Compared with the vast analytical work, experimental tests uniquely for developing seismic design guidelines for nonstructural components (excluding the tests for facility qualifications) and the research work based on field observations of instrumented buildings are very limited [16,17]. The most comprehensive and systematic early work for nonstructural components involving the data collected from instrumented buildings was carried out in 1990s [18–22]. In the early investigations, a total of 405 floor motion datasets were compiled, taken from 16 California earthquakes, ranging from the 1971 San Fernando Earthquake to the 1994 Northridge Earthquake. Based on these investigations, major changes were made for seismic design of nonstructural components in the 1997 Edition NEHRP Provisions [23] and their recommendations have been subsequently adopted in ASCE/SEI 7-10 [24]. In addition, UBC 1997 [25] provides design recommendations for calculating seismic design forces of nonstructural components. More recently, Fathali and Lizundia [26] expanded the floor motion database collected from the instrumented buildings and developed improved design models for nonstructural components. While the existing design models have different forms,



(a) Beam-to-column connection and brace-to-column connection

(b) Tension-only brace

Fig. 1. Key design details of the new CBF system.