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Design and behavior of zipper-braced frames

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Abstract

This paper proposes a design methodology for zipper-braced frames aimed at achieving ductile behavior. Three zipper-braced models were designed on the basis of the proposed design procedure to carry the same masses as the 3-, 9-, 20-story SAC model buildings with moment-resisting frames designed for the Los Angeles area. Pushover analyses of the models were performed to estimate the overstrength, inelastic strength and deformation capacities for the entire structures, and assess the sequence of yielding and buckling in the members. The performance of the models was also evaluated using nonlinear dynamic analyses under an ensemble of 2%-in-50-year pulse-type near-fault ground motions. The analyses indicate that the design procedure produces safe designs, with the design becoming more conservative as the number of stories increases. The distribution of interstory drifts demonstrates the efficiency of the zipper struts in achieving uniform damage over the height of the structure, and generally satisfies allowable interstory drift ratio limits.

Keywords: Steel frames; Seismic design; Steel; Struts; Nonlinear analysis; Earthquake resistance structures; Structural models

1. Introduction

Braced frames are economical and efficient structures for resisting lateral loads. A typical braced frame configuration is the so-called inverted chevron-braced (inverted-V-braced) one shown in Fig. 1(a), which provides an opening in the middle of the story and is thus preferred by architects and owners over the concentrically braced options. In general, the performance of these systems is governed by the buckling behavior of the inclined members in compression. For wind design, it is typical to assume a tension-only behavior and the compressive strength of these braces is ignored. For seismic design, where the design is controlled by large cyclic drifts and the need for energy dissipation, the alternating buckling and yielding of the braces leads to poor hysteretic behavior, the formation of a soft story mechanism [Fig. 1(b)] and associated potential collapse. Thus braced frames have traditionally not been considered a suitable system in high seismic areas unless the buckling and yielding are controlled in the design through the use of both bracing members with low slenderness both at the local and global levels, and large beams to sustain the unbalanced vertical forces resulting from brace buckling.

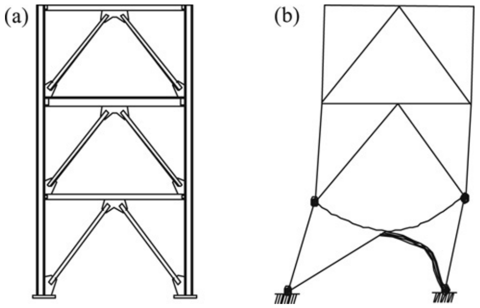

Fig. 1. (a) Inverted-V-braced configuration; (b) formation of a soft story mechanism.

To counteract the tendency of chevron-braced frames to form soft story mechanisms in the first floor, Khatib et al. [1] proposed the addition of zipper columns (zipper struts) between the brace locations at the midspan of floor beams. These zipper struts transfer the unbalanced vertical forces at this location induced by buckling of the braces into the stories above. The result is the formation of a full-height collapse mechanism that provides substantial additional strength and ductility to an otherwise brittle system. Although this system has been mentioned in the AISC Seismic provisions for several editions [2], a comprehensive design procedure has not been

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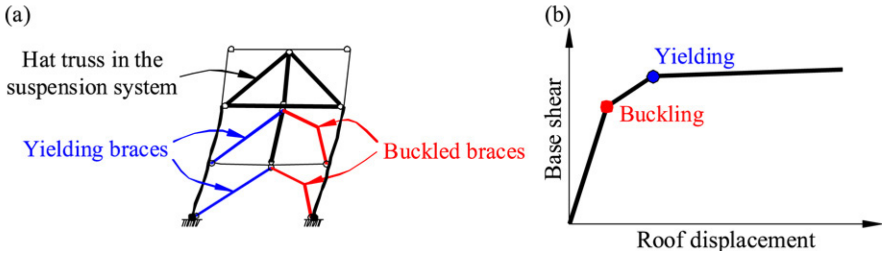

Fig. 2. Expected behavior and performance of zipper frames.

available. Khatib et al. [1] proposed that the design force for the zipper column at any story be taken as the minimum of either a square root of the sum of the squares (SRSS) approximation of the unbalanced vertical forces that can be transmitted from the stories below or a SRSS approximation of the unbalanced vertical forces at the stories above and the story under consideration. Tremblay and Tirca [3,4] recently proposed another design methodology for zipper struts based on a full-height zipper mechanism by considering different scenarios of brace buckling sequences and subsequent force redistribution. However, their analytical studies showed that instability and collapse occurred when the frames were subjected to severe near-fault earthquake motions. These failures followed the buckling of all compression braces, as the large resulting unbalanced vertical forces were reapplied to the floor beams, which were not originally designed to resist these forces.

To overcome this behavior, Leon and Yang [5] proposed a design procedure using a partial-height zipper mechanism and a hat truss system in the top story. The latter was used to prevent the formation of a full collapse mechanism and to redirect the unbalanced vertical forces into the exterior columns. Several experiments on reduced-scale zipper frame specimens designed according to the preliminary design procedure have been performed by a variety of testing methods [6–12]. The experimental results showed excellent strength and ductility behavior for the zipper-braced frames. These results were consistent with those of refined 2D and 3D numerical simulations conducted using the Open System for Earthquake Engineering Simulation (OpenSEES) [13], an open-source platform widely used in the USA for this type of studies.

This paper proposes a refined design methodology for zipper-braced frames with partial-height zipper mechanisms in view of the experimental results from this collaborative project. Three zipper-braced models proportioned according to the new design methodology are studied to validate the adequacy of the design based on the performance of both individual members (zipper struts and top-story braces) in terms of strength and of the overall frame in terms of interstory drifts.

2. Design methodology for zipper-braced frames

2.1. Design philosophy

The basic design objective for a zipper-braced frame is to mitigate the typical soft-story mechanism associated with braced frames by distributing more uniformly both story drift and energy dissipation over the height of the building. There are three main components of this innovative system. The first component is the zipper strut which forces simultaneous buckling of all stories except the top one, and leads to tension yielding of all braces [Fig. 2(a)]. The second component is the hat truss, which prevents the formation of a full plastic mechanism and thus provides large deformation capacity. The third component consists of the exterior columns, which transmit the forces back to the foundation.

From the standpoint of base shear versus roof drift response, a properly designed zipper-braced frame should exhibit trilinear response with large ductility, as shown in Fig. 2(b). As presented in Fig. 2(a), simultaneous buckling in the compression braces significantly reduces the initial stiffness of the frame. However, the strength of the whole frame continues to increase, first reaching its yielding strength and then entering a hardening range due to the yielding in the tension braces. The proposed design provisions are presented next, including a short commentary.

2.2. Design procedure

The design of zipper-braced frames shall consist of a two-step procedure. The first is a strength design phase for the braces in which the presence of the zipper elements is ignored. The second is a capacity design phase in which the zipper struts are added and other structural elements are redesigned except for the braces below the top-story level.

2.2.1. Phase I (strength design)

The braces shall be designed, to resist the effects of earthquake and vertical loadings, from the load combinations stipulated by the Applicable Building Code without the aid of the zipper struts.

Commentary: This phase follows the conventional Special Inverted-V-Braced Frame (SIVBF) design procedure. The braces are assumed to resist all the lateral loads, with the critical compression braces designed to carry a force equal to $\phi_c A_g F_{cr}$*. This phase fixes the sizes of the braces in all stories except the top story. Preliminary design for the other elements should be carried out, but the design of the beams shall ignore the shear force at the centerline resulting from the unbalanced forces induced by the braces.*

2.2.2. Phase II (capacity design)

In this phase, the zipper struts are added and other structural elements are redesigned except for the braces below the top-story level. The frame designed in Phase I is further