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# Design and seismic response of modified suspended zipper braced frames

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ABSTRACT

In a conventional suspended zipper braced frame (SZBF), the required strength of zipper columns and top story braces increases rapidly with the number of stories, resulting in unacceptable cross sections for these members. To overcome these drawbacks, a new modified suspended zipper braced frame (RZBF) is proposed in this paper. Compared with SZBF, the two central ideas of RZBF are that the unbalanced vertical forces at each story do not reach the maximum values simultaneously, and that the braced beams can transfer part of the unbalanced vertical forces during earthquakes. In order to understand better the seismic performance and design advantages of RZBF, nonlinear time history analyses were conducted on 3, 6, 10, 15, and 18-story RZBF and SZBF models. Comparison of the results obtained demonstrates the efficiency and viability of RZBF. Moreover, it is shown that the RZBF saves more steel material as the number of stories increases.



## 1. Introduction

The conventional chevron braced frame is a commonly used type of concentrically braced steel frame. During earthquakes, the compression brace buckles and loses its compressive strength, whereas the tension brace continues increasing axial force. This creates an unbalanced vertical force on the braced beam. In order to prevent undesirable deterioration of lateral strength of the frame, current design codes [1–3] require that the braced beam shall possess adequate strength to resist this unbalanced vertical force in combination with appropriate gravity loads, requiring very strong braced beams and therefore relatively inefficient structure [4–5]. Furthermore, even when braced beams are strengthened, conventional chevron braced frames are still prone to soft-story mechanisms in the lower stories during earthquakes [6]. The adverse effect of this unbalanced vertical force can be mitigated by adding zipper columns (i.e. vertical members linking to the brace-to-beam intersecting points), which was first proposed by Khatib in 1988 [6]. This structural system is labeled "zipper braced frame" as shown in Fig. 1. The main purpose of installing zipper columns is to force all compression braces in a braced bay to buckle almost simultaneously and thereby transfer any unbalanced vertical forces into the stories above. This will result in a more uniform distribution of damage throughout the height of building.

The zipper column is the main factor in the difference of seismic performance between the conventional chevron braced frame and the zipper braced frame. Khatib et al. [6] suggested that the design tension force of the zipper column at any story should be taken as the minimum value of the following: 1) a square root of the sum of the squares (SRSS) rule of the unbalanced vertical forces that can be transmitted from the stories below, and 2), a SRSS rule of the unbalanced vertical forces that can be transmitted from the stories above and the story under consideration. Sabelli [7] recommended that the zipper columns should possess the same compression and tension strengths as the braces located at the level below. Considering different scenarios of brace buckling sequences and subsequent force redistribution, Tremblay and Tirca [8,9] proposed a design method to predict the forces of zipper columns. Tirca and Chen [10,11] refined the design method proposed by Tremblay and Tirca [8,9] with consideration of six lateral load distribution patterns. In the zipper braced frames above, if all compression braces buckle almost simultaneously, the full-height zipper mechanism forms, resulting in the occurrence of structural instability or collapse [8]. To avoid these failures, Leon and Yang [12,13,14] proposed a suspension system, labeled as a suspended zipper braced frame (SZBF). In a SZBF, the zipper column is a tension member and designed to resist all the vertical forces from the framing members below. The top story braces are designed to remain elastic even after all the braces below have buckled or yielded. By providing a strong braced frame in the top story, namely a hat truss system, the full-height zipper mechanism is avoided. A series of experiments and numerical analyses had been performed to evaluate the seismic performance of SZBF [13–19]. The results show that the SZBF exhibited great strength and ductility behavior during earthquakes. However, as the number of stories increases, the required strength of zipper columns in upper stories and top story braces becomes very large, resulting in unacceptable

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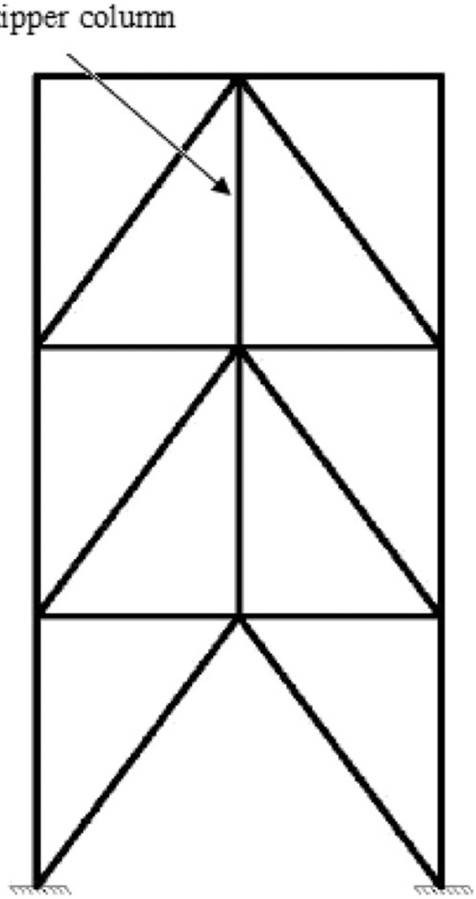


**Fig. 1.** Zipper braced frame.

cross sections [20]. In order to mitigate this disadvantage, Razavi [21] proposed using high-strength, pre-stressed cables as zipper columns.

Although the zipper braced frame has been mentioned in AISC341-10 Seismic provisions for Structural Steel Buildings [2] and the Chinese seismic design code GB50011 [1], a specific design recommendation has not been presented as yet. Hence, in this paper, a new modified suspended zipper braced frame (RZBF) is proposed. Five RZBF and SZBF models with 3, 6, 10, 15, and 18 stories were designed and analyzed using nonlinear time history analyses when subjected to both frequent and rare earthquakes. In order to evaluate the design advantages of RZBF, the seismic behavior of RZBF was compared with that of SZBF.

## 2. Design procedure for RZBF

Similar to SZBF, the design procedure of RZBF is divided into two steps. The first step is strength design phase, which is the same process used in SZBF design [16]. In the second step, the zipper columns are linked to the structure. Design methods used for the top story braces and braced columns correspond with those used in SZBF. Considering the effect of higher modes of oscillation, the phenomenon that the unbalanced vertical forces at each story, due to brace buckling, reach the maximum values almost simultaneously over the building height shall not be fully realized during rare earthquakes. Accordingly, the tension force estimation of the zipper columns by direct addition of the unbalanced vertical forces below the story is likely conservative. Meanwhile, the braced beams can also transfer part of the unbalanced vertical forces. Based on these considerations, two empirical formulae for calculating the design axial tension forces of zipper columns, as shown in Eqs. (1) and (2), are suggested. By using the two formulae, the axial tension forces of zipper columns in the lower five stories are directly added whereas those in the upper stories are combined by the SRSS rule. Taking a 7-story zipper braced frame as an example, Fig. 2 illustrates this method.

$$N_{i+1} = N_i + (V_i\text{-}F_i) \qquad i = 1, 2, 3, 4 \tag{1}$$

$$N_{i+1} = \sqrt{N_i^2 + (V_i\text{-}F_i)^2} \qquad i = 5, \ldots, N \tag{2}$$

where $V_i$ is the unbalanced vertical force due to brace buckling at the $i$th story; $F_i$ is the unbalanced vertical force transferred by the braced beam at the $i$th story, which is the residual capacity subtracting the required strength from the design strength of the braced beam. In this paper, $F_i$ is back-calculated according to the strength and stability design formulae provided in Chapter 9 of the GB50017 code [22]. The formulae for calculating $F_i$ are as follows:

Strength design:

$$\frac{N_i}{A_{ni}f} \le 0.13 \qquad F_{1i} = \frac{4\left[W_{pnxi}f - M_{xi}(q_G)\right]}{l} \tag{3}$$

$$\frac{N_i}{A_{ni}f} > 0.13 \qquad F_{1i} = \frac{4\left[1.15\left(1 - \frac{N_i}{A_{ni}f}\right)W_{pnxi}f - M_{xi}(q_G)\right]}{l}. \tag{4}$$

In-plane stability design:

$$F_{2i} = \frac{4\left[\left(1 - \frac{N_i}{\varphi_{xi}A_i f}\right)\frac{W_{pxi}f}{\beta_{xi}}\left(1\text{-}0.8\frac{N_i}{N'_{Exi}}\right) - M_{xi}(q_G)\right]}{l}. \tag{5}$$

Out-plane stability design:

$$F_{3i} = \frac{4\left[\left(1 - \frac{N_i}{\varphi_{yi}A_i f}\right)\frac{\varphi_{b_i}W_{pxi}f}{\eta_i\beta_{txi}} - M_{xi}(q_G)\right]}{l} \tag{6}$$

$$F_i = \min(F_{1i}, F_{2i}, F_{3i}). \tag{7}$$

Where $M_{xi}(q_G)$ is the bending moment at mid-span of the braced beam in the $i$th story induced by the gravity loads; $N_i$ is the maximum axial compression force of the braced beam in the $i$th story, generated by the brace yielding and brace post-buckling force; and $l$ is the span of the braced beam. Other symbols are defined and determined in accordance with the specification of the GB50017 code [22]. If the requirements that the instability will not appear for the braced beam are satisfied, $F_i$ is equal to $F_{1i}$.

## 3. Design of the buildings

To assess the seismic behavior of RZBF and compare it with SZBF, five office buildings with 3, 6, 10, 15, and 18 stories, were studied. The buildings were assumed to be located in a region with a seismic intensity of VIII (design basic acceleration of ground motion: 0.2 $g$), seismic design group II, and site class III, according to the requirement of the GB50011 code. The height of each story was 3.9 m. The columns were taken to be pinned at their base but capable of carrying moments along the whole height of the buildings, and the beams were assumed to be pin-connected to the columns. Fig. 3 shows the plan and elevation views of the buildings studied.

For design purposes, the loads were composed of gravity loads, consisting of the dead loads plus 50% of the live loads, and horizontal seismic loads. The nominal values of the dead loads and the live loads were 5.5 kN/m$^2$ and 2.0 kN/m$^2$, respectively. The nominal seismic loads were calculated using the mode superposition response spectrum