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Design of Zipper Column in Inverted V Braced Steel Frames

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ABSTRACT :
Inverted V (or chevron) braced steel frames have been seen as being prone to soft story response once the compression brace buckles under earthquake loading. To salvage chevron braced frames, the concept of the zipper column was proposed many years ago such that the zipper column can redistribute the inelastic demand over the height of the building. However, it appears that a rational design method for the zipper column has not been established yet. In this paper, a simple static design was first presented, and then a dynamic design method which can consider the effects of the brace slenderness and higher modes was proposed by combining the refined physical theory braced model and the modal pushover analysis. Inelastic dynamic analysis showed that both the static and dynamic design methods proposed in this study result in significantly improved seismic performance as compared to the case without zipper column. The simple static design method proposed to invoke at least two-story buckling mechanism equally worked well in this limited case study.

KEYWORDS:
Inverted V (chevron) braced steel frames, Zipper column, Modal pushover, Seismic

1. INTRODUCTION

A popular configuration of the concentrically braced frame is the inverted V-braced frame (IVBF) since it is amenable to many architectural requirements. However, under severe earthquake loading, the compression brace buckles and loses its axial strength while the force in the tension brace continues to increase up to the point of the yielding. This imposes significant unbalanced vertical force on the intersecting beam as well as its connections and supporting members and may lead to forming weak stories. In order to reduce the likelihood of weak story formation, seismic provisions usually require that the beam possess adequate strength to resist significant postbuckling unbalanced force (for example, AISC 2005). This design requirement generally results in very heavy-sized beams. Alternatively, the zipper column proposed by Khatib et al. (1988) may be used to mitigate the adverse effects of postbuckling force redistribution as shown in Figure 1. The role of the zipper column is to induce simultaneous buckling of braces over the height of a building. This configuration results in a better hysteretic response and more uniform energy dissipation over the height of the building.

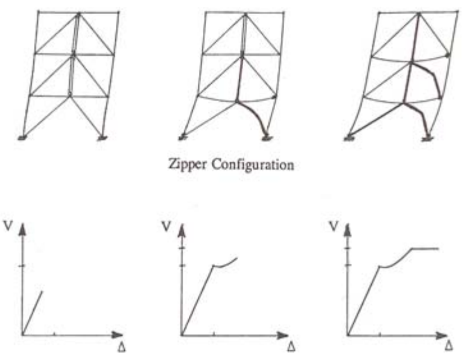


Figure 1 Improved performance by zipper column configuration (Khatib et al 1988)

However, currently the design procedure for the zipper column in multi-story IVBF is not clear. Especially a rational procedure to estimate seismic force demand in the zipper column needs to be established. In estimating the postbuckling unbalanced load for use in designing the zipper column, it is usually assumed that the tension brace yields while the compression brace reaches its residual postbuckling strength. The residual postbuckling strength for typical bracing members as suggested by the current AISC Seismic Provisions is 30 % of the initial buckling strength. However, as indicated by Tremblay (2002), the residual postbuckling strength of braces under cyclic loading varies with the brace slenderness ratio (see Figure 2). Furthermore, in multi-story braced frames, higher modes often have significant effects on overall response and should be considered properly in design. In this study, the refined physical theory model developed by Ikeda and Mahin (1984) is used to consider the brace slenderness effects in designing the zipper column. To include the effects of higher vibrational modes, the modal pushover analysis recently proposed by Geol and Chopra (2004) is used.

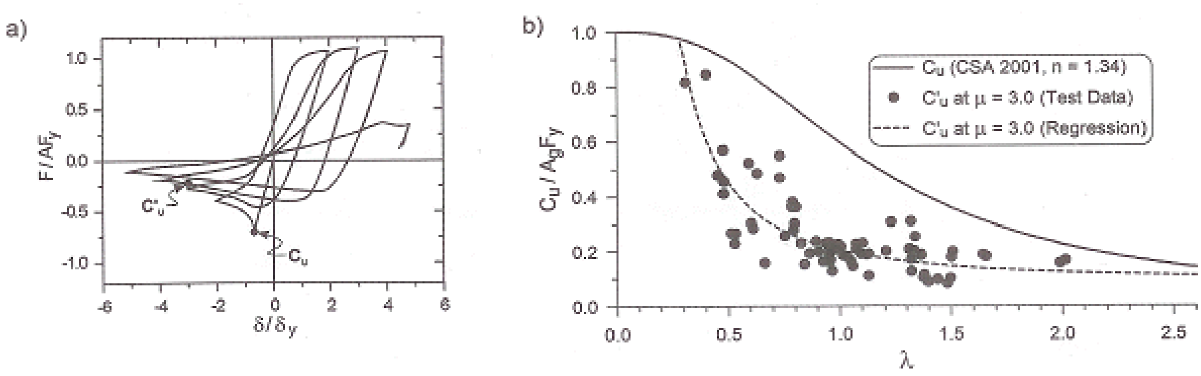


Figure 2 Cyclic behavior of bracing members and residual postbuckling strength [Tremblay, 2002]

2. TWO DESIGN METHODS PROPOSED

From the capacity design perspective, braces are "fuse" elements of the frame, and all other elements including the zipper column should be designed to be elastic for the maximum forces imposed by the braces during cyclic yielding and buckling. Two design methods, or static versus dynamic, will be presented in the following.

2.1. Static Design Method

Figure 3 shows free body diagram to calculate the vertical unbalance force after the compression brace buckles. The use of rigorous capacity design procedure may be too conservative for the zipper columns in the upper part of medium to high-rise buildings because the braces in each story will not buckle simultaneously. One simple approach that may be tried is to size the zipper column at each story for the unbalanced load coming from just one story below. This method seeks to invoke, at least, two-story buckling mechanism. In this method, no dynamic information is needed in designing the zipper column. The unbalanced force may be calculated using $T_y (= R_y A_g F_y)$ for tension brace and $C_u`(= 0.3A_g F_{cr})$ for compression brace as suggested by the AISC Seismic Provisions. The material overstrength factor (R_y) is assumed to be 1.0 in this study for direct comparison with the dynamic method in the below. Or, the area of the zipper column is simply given as

$$A_{static} = \frac{(T_y - C_u^{'}) \sin\alpha}{\phi F_y} \tag{1.1}$$

Where $T_y (= R_y A_g F_y)$ = tensile yield strength of tension brace, $C_u`(= 0.3A_g F_{cr})$ = residual postbuckling strength, α = angle of diagonal brace, ϕ = strength reduction factor (0.90), and F_y = yield strength of the zipper column.

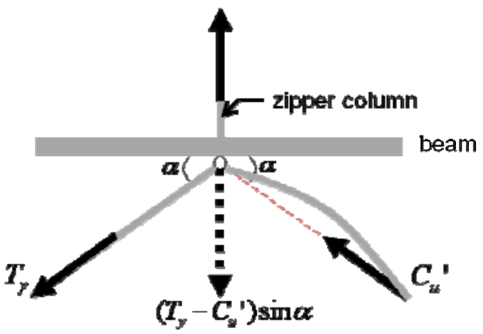


Figure 3 Postbuckling vertical unbalance force

2.2. Dynamic Design Method

As mentioned previously, the dynamic design procedure proposed in this study considers both the effect of the brace slenderness and higher mode effects by using the refined physical theory brace model (Ikeda-Mahin 1984, Pascal, T. 1995) and the modal pushover analysis (Chopra and Goel 2004). Detailed descriptions on the the refined physical theory brace model and the modal pushover analysis are omitted here due to space limitations. The dynamic design method we propose can be summarized in the step-by step manner as follows:

(1) First, design the inverted V braced frame (with no zipper columns) to resist the effects of earthquake and vertical loading per relevant seismic design provisions.
(2) Compute the axial force of the zipper column for each mode by the modal pushover analysis.
(3) Compute the design axial force of the zipper column by using the square-root-of-sum-of-squares (SRSS) of each modal axial force up to 90% effective cumulative mass per equation (2.1).
(4) Size the zipper column per equation (2.2).
(5) Repeat the steps (2) though (4) until the size of the zipper column converges.

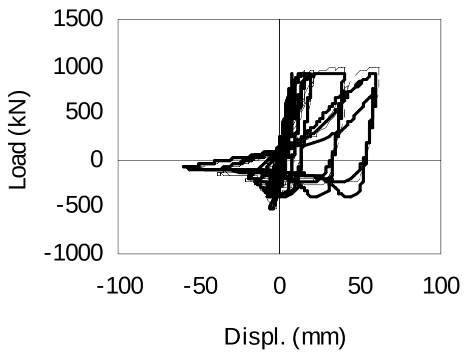
$$F_i = \sqrt{\sum_{j=1}^{N}\left(F_{ij}\right)^2} \tag{2.1}$$

$$A_{gi} = \frac{F_i}{\phi F_y} \tag{2.2}$$

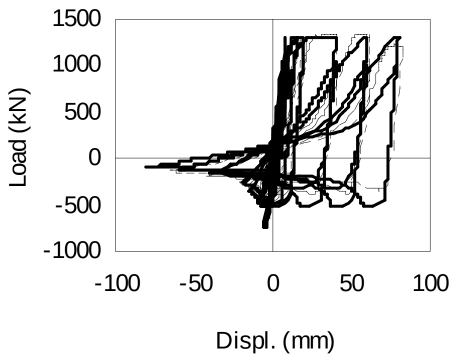
Where N= number of modes used in the SRSS procedure, F_i : design axial force of the zipper column at the ith story, F_{ij} = axial force of the zipper column at the ith story contributed by the jth vibration mode, A_{gi} = Area of the zipper column at the ith story, ϕ = strength reduction factor (0.90), and F_y = yield strength of the zipper column.

3. CALIBRATION OF THE REFINED PHSICAL THEORY BRACE MODEL

The refined physical theory brace model (RPBM) developed by Ikeda and Mahin (1984) can reasonably simulate several important phenomena observed during the inelastic cyclic loading of braces, such as progressive deterioration of the compression buckling strength and residual elongation due to plasticity. The model is based on an analytical expression of the axial force versus axial displacement and divides a hysteretic cycle into six possible zones of behavior over which simple formulations are used to approximate the physical characteristics. Taddei (1995) implemented the Ikeda and Mahin model in Drain-2DX. To use RPBM in Drain-2DX analysis, this model needs to be provided with information about P-M interaction curve, the axial force vs. tangent modulus of elasticity, and the axial force vs. plastic hinge rotation curve. This set of information should be calibrated based on results from experiments. Two full-scale cyclic tests on steel braces of hollow section (Han et al, 2007) were used for calibration in this study. Figure 4 shows that the calibrated RPBM in Drain-2DX can stimulate the overall cyclic buckling behavior very well. The calibrated RPBM were used in the modal pushover analysis for design and also evaluating seismic performance by nonlinear dynamic analysis in the following.



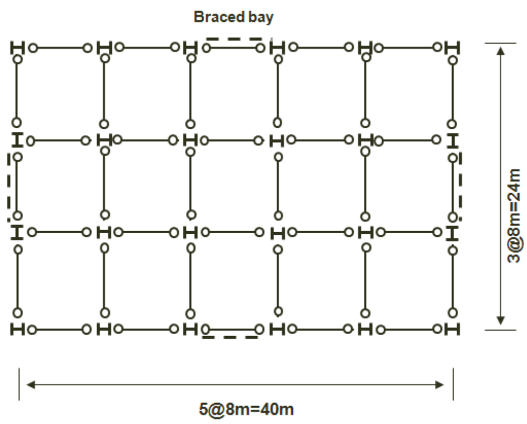
(a) HSS 100x100x6,Kl/r=85



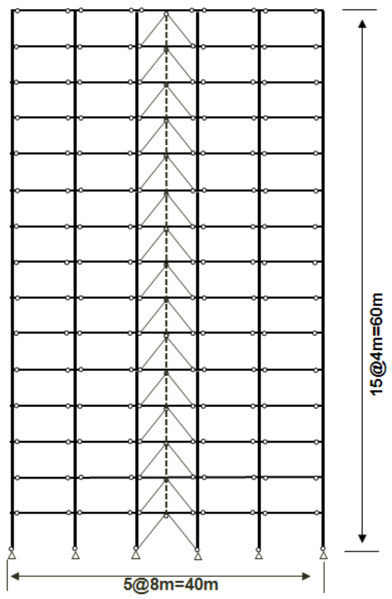
(b) HSS 100x100x9, Kl/r=90

Figure 4 Comparison of experimental and numerical results (---: experimental, — : numerical)

4. DESIGN OF FRAME FOR CASE STUDY



(a) Floor plan



(b) Elevation

Figure 5 Floor plan and elevation

Three 15-story buildings were designed for a case study. Figure 5 shows the structural floor plan and elevation. IVBF (without zipper column) was first designed and the design was modified with inserting the zipper columns designed according to the two design methods presented previously. The design response spectrum was the Newmark median spectrum (5% damping). All beam-to-column connections were assumed to be pinned. Uniformly distributed floor dead loads of 5.0 kN/m^2 and live loads of 2.5 kN/m^2 were applied. The response modification factor (R) was assumed as 6.0. The design seismic base shear was 19.6 % of the building weight. The first three vibration periods of the structures were 3.06, 0.811, and 0.423 sec. The effective modal mass factors for the first three modes were 0.70, 0.19, and 0.05, or the cumulative effective mass up to the 3rd mode was 0.94. Thus the SRSS for computing the axial force of the zipper column was conducted up to the 3rd mode.

The dynamic design method required three iterations to research convergence. The selected member sizes for the three frames are listed in Table 1. The difference of total steel tonnage of the zipper column between the static and dynamic methods was about 15%. The dynamic method required heavier sections in the lower middle part of the frame.

Table 1 Selected member sizes of 15-story building

Story	Braces	Columns	Beams		Zipper columns	
			Without zipper column	With zipper column	Per static design	Per dynamic design
15	HSS5x5x1/2	W10x77	W40x149	W40x149*	W8x18	W8x21
14	HSS5x5x1/2	W10x77	W40x149	W16x31	W8x18	W8x21
13	HSS6x6x5/8	W12x152	W40x149	W16x31	W8x28	W8x18
12	HSS7x7x5/8	W12x152	W40x149	W16x31	W8x28	W8x13
11	HSS7x7x5/8	W12x152	W40x149	W16x31	W8x31	W8x21
10	HSS8x8x5/8	W14x257	W40x199	W16x31	W8x35	W8x35
9	HSS9x9x5/8	W14x257	W40x199	W16x31	W8x35	W8x67
8	HSS9x9x5/8	W14x257	W40x199	W16x31	W8x35	W8x67
7	HSS9x9x5/8	W14x342	W40x199	W16x31	W8x35	W8x67
6	HSS9x9x5/8	W14x342	W40x199	W16x31	W8x35	W8x67
5	HSS9x9x5/8	W14x342	W40x199	W16x31	W8x35	W8x58
4	HSS9x9x5/8	W14x398	W40x199	W16x31	W8x35	W8x40
3	HSS9x9x5/8	W14x398	W40x199	W16x31	W8x35	W8x35
2	HSS9x9x5/8	W14x455	W40x199	W16x31	W8x35	W8x24
1	HSS9x9x5/8	W14x455	W40x199	W16x31		

* The roof beam was designed to resist the postbuckling unbalance force

5. COMPARISON OF SEIMSIC PERFORMANCE

In order to examine the seismic performance of the three frame models, nonlinear dynamic analysis was conducted by using the Drain2-DX program. P-△ effect was considered by including the fictitious leaning column subjected to gravity loading and 5% Rayleigh damping was specified. Ten inelastic dynamic analyses by using the scaled SAC suite of ground motions (LA21~LA30, Somerville et al 1997) were performed for each frame. The ground motions were scaled to match the design spectral response acceleration at the structure fundamental period. The mean values of the peak interstory drift ratios are presented in Figure 6.

As shown in figure 6, both the static and dynamic design methods proposed in this study lead to significantly improved seismic performance as compared to the frame without zipper column, especially lower and upper part of the frame: the interstory drifts at the first story and the 14th story were reduced from 0.023 to 0.012 radian and from 0.036 to 0.020~0.023 radian, respectively. The dynamic method showed only slightly improved (or more uniform) distribution of interstory drifts over the building height, although the design procedure was much more effort-demanding. The simple static design method proposed to invoke at least two-story buckling mechanism equally worked well in this limited case study.

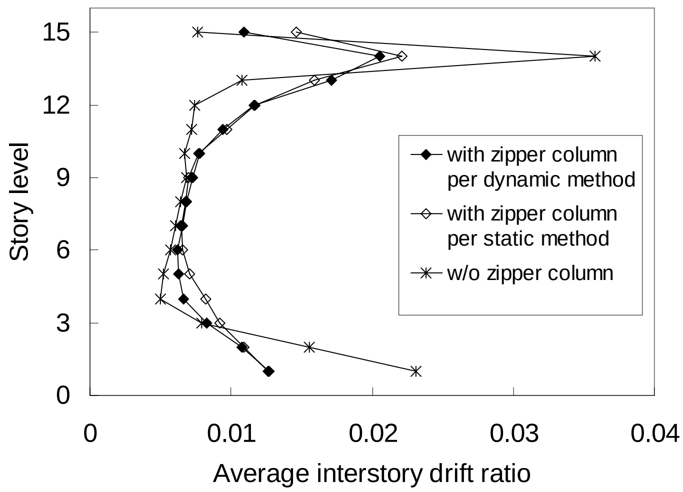


Figure 6. Comparison of Interstory drift ratio

5. SUMMARY AND CONCLUSIONS

In this study, two design methods of the zipper column to salvage inverted V braced frames were presented and evaluated based on a limited case study.

From the capacity design perspective, it is reasonable to design the zipper column to be elastic for the maximum forces imposed by the braces during cyclic yielding and buckling. But, the use of rigorous capacity design procedure is too conservative for most of the zipper columns since the braces in each story will not buckle simultaneously. Considering this, a simple static method which sizes the zipper column at each story for the unbalanced load coming from just one story below was first proposed. This method aims at invoking at least two-story buckling mechanism. The dynamic design method proposed considers both the effect of the brace slenderness and higher mode effects on the postbuckling behavior by incorporating the refined physical theory brace model and the modal pushover analysis in the design procedure. This method is theoretically more appealing but much more effort-demanding.

Inelastic dynamic analyses for 15-story frame building showed that both the static and dynamic design methods proposed lead to significantly improved seismic performance as compared to the frame without zipper column. The dynamic method showed only slightly improved (or more uniform) distribution of interstory drifts over the building height. The simple static design method proposed equally worked well in this limited case study. Further studies based on extensive inelastic dynamic analysis with including diverse structural configuration and earthquake input are needed to critically evaluate the effectiveness of the two design methods proposed.

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