Lateral Force Distributions in Multistory Braced-Moment Frames

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ABSTRACT

Braced frames traditionally have been analyzed and designed as trusses with all joints modeled as pins, such that only the braces provide lateral force resistance. However, frames with gusset plate connections create a rigid joint zone between frame beams and columns, effectively resulting in moment frame behavior, particularly at larger drift angles when the braces have yielded or buckled. Described herein is a rationale for multistory braced-moment frames that includes the frame's moment resistance to lateral displacements when subjected to story-drift angles where the lateral resistance of the frame comprises both brace and moment frame action.

Keywords: braced-moment frame, lateral force distribution.

INTRODUCTION

Braced frames are typically modeled and designed as pinned connected truss members, wherein all lateral resistance is provided by the braces (Muir and Thornton, 2014). The design of the gusset plates is subsequently based upon only the transfer of the brace forces to the pin-connected beams and columns. This design rationale has proven acceptable for story-drift angles at and below that which induces yielding in the braces. However, at story-drift angles of approximately 0.0025 (1/400) rad, the braces yield, as shown in the single-story frame pushover analysis in Figure 1, and additional lateral displacement is resisted by moment frame action (Walters et al., 2002). Designers of braced frames often ignore the frame action or mitigate it by introducing simple or semi-rigid connections in the braced frame, as discussed in the AISC *Seismic Provisions* Commentary Section F2.6b (2016b). Described herein is a design rationale for mutistory buckling restrained braced frames (BRBF) that includes the moment frame action of the braced frame to lateral loads after the braces have yielded (Richard et al., 2024).

Shown in Figure 2 is a single-story, braced-moment frame (a) modeled for analysis of the lateral force distribution as a combination of the force distributions in a braced frame (b) and a moment frame (c). The force distributions in Figures 2(b) and (c) are based upon a frame drift angle that results in the yielding of the braces in Figure 2(b) and inelastic action in the top and bottom beams in Figure 2(c), based on strong column-weak beam frame design (Richard et al., 2024). Beam plastic hinges as shown are located at the ends of the gusset plates as shown by both test and analyses (Lopez et al., 2002, 2004; Richard et al., 2017).

ANALYSIS OF MULTISTORY BRACED-MOMENT FRAMES

Shown in Figure 3 is a four-story braced frame with all gusset plate connections replaced with pins for analysis (Uniform Force Method). This truss model disregards the moment frame resistance after the braces yield shown in Figure 1.

Figure 4 depicts a virtual lateral displacement for this frame with plastic hinges located in the beams for strong column-weak beam design.

Lateral force distributions in multistory braced frames are analyzed herein using the single-story rational applied to each story as shown in Figures 2(b) and (c) (Richard et al., 2024). As shown in Figure 4, the virtual lateral frame displacement where the columns remain straight is based upon a strong column-weak beam frame design with two plastic beam hinges for each story. For each story, the moment frame shear, V_m, is determined using the virtual work equation where external work (EW) is equal to the internal work (IW). For a story drift, Δ, a story moment frame shear, V_m, a beam moment, M_b, and two beam hinge rotations θ_{hinge}, the virtual work equation is:

$$V_m \Delta = 2 M_b \theta_{hinge} \tag{1}$$

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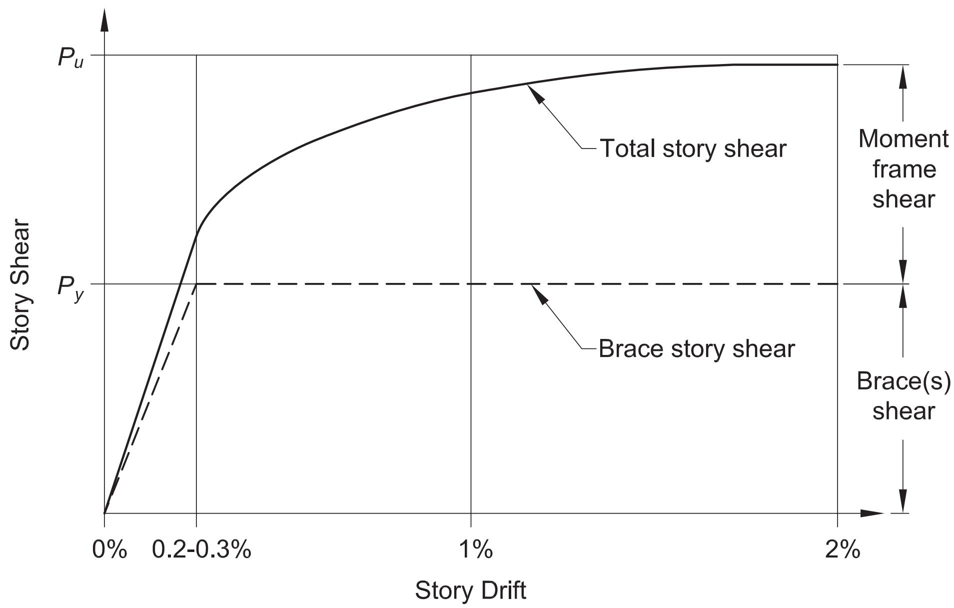

Fig. 1. Typical story shear distribution in a braced frame pushover analysis.

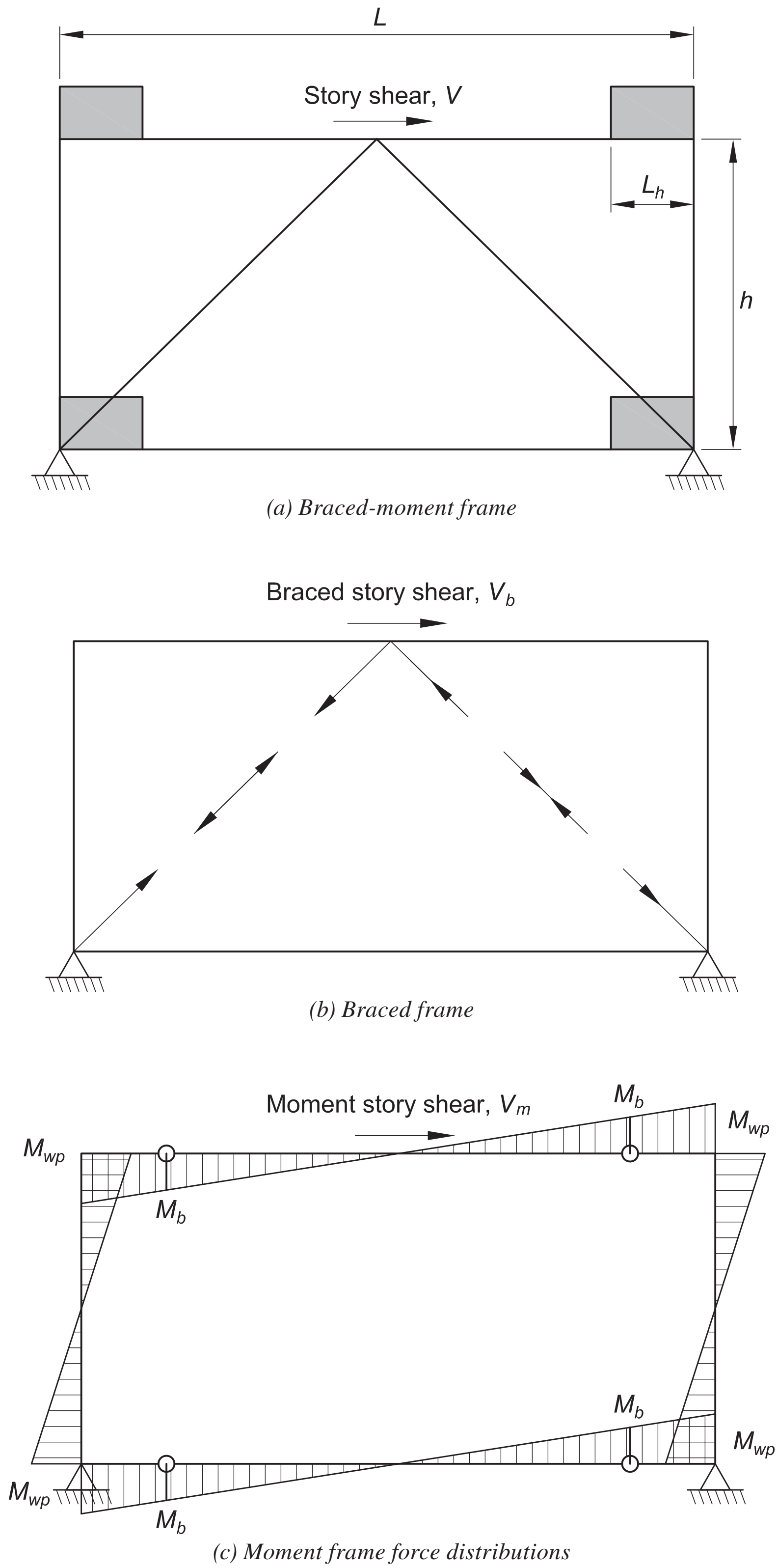

Fig. 2. Single-story frame.

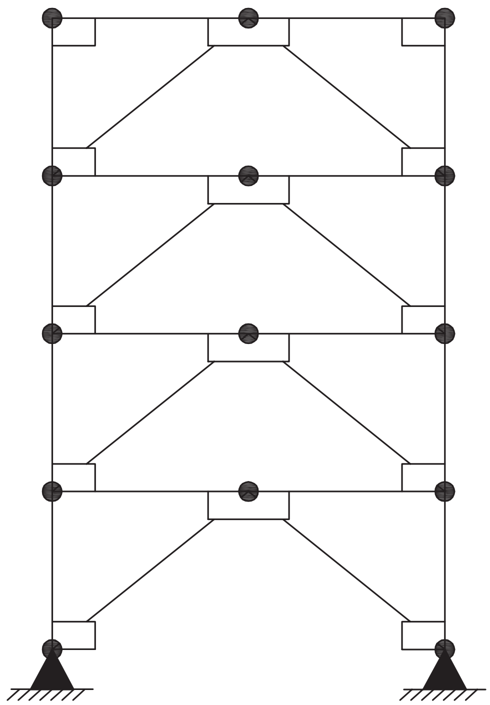

Fig. 3. Braced-moment frame with UFM pin connections.

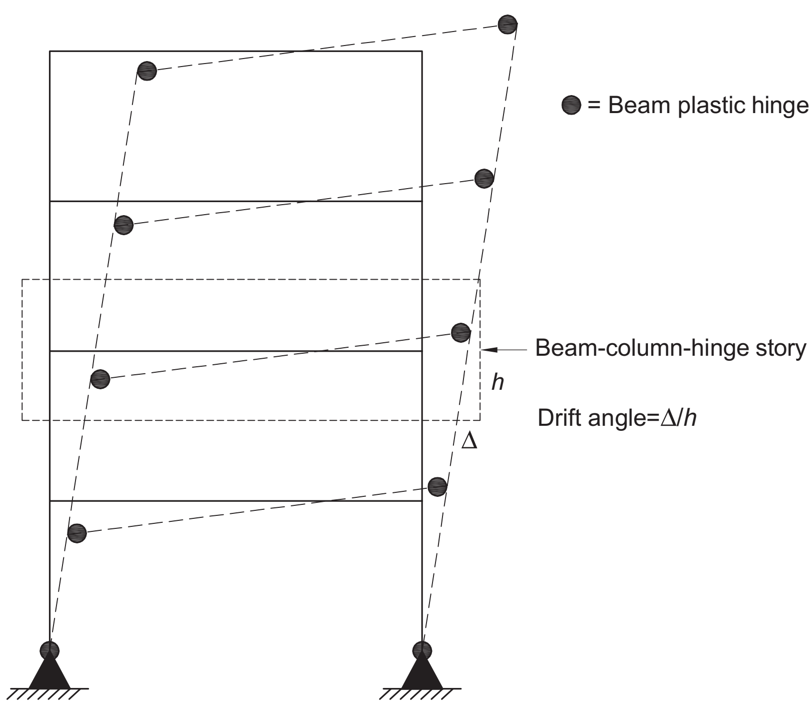

Fig. 4. Moment frame beam plastic hinge locations.

The plastic hinge rotation in terms of the story drift angle, θ, is:

$$\theta_{hinge} = \theta k_1 = \frac{\Delta k_1}{h} \tag{2}$$

where the constant k_1 is defined in Appendix A and h is the story height.

The beam hinge plastic moment, M_b, is determined as follows:

$$M_b = M_u k_2 \tag{3}$$

where k_2 is a material term that adjusts the pure bending plastic hinge moment, M_u, to account for axial-moment interaction. The derivations of k_1 and k_2 are presented in the appendix of this paper. Substituting Equation 2 and Equation 3 into Equation 1 gives the story shear for the moment story frame in Figure 2(c).

$$V_m = \frac{2 M_u k_1 k_2}{h} \tag{4}$$

In Figure 4 with the moment frame story shear, V_m, known, the brace frame story shear, V_b, is determined as:

$$V_b = V - V_m \tag{5}$$

where V is the frame story shear. The design of the braces is based upon their expected yield stress. This rationale provides the forces in the braces, beams, and columns to design the gusset plates based upon a braced-moment frame force distribution.

DESIGN EXAMPLE—BRACED-MOMENT FRAME ANALYSIS

Given:

Analyze the single-bay, four-story braced frame shown in Figure 5. The beam, column, and gusset plate material is ASTM A992/A992M (2022) (F_y = 50 ksi). The frame bay width is 30 ft and the story height is 15 ft. Gusset plates are 24 in. × 24 in. The force distributions shown use the equivalent lateral force method given in ASCE/SEI 7 (2016) with a base seismic shear of 600 kips. (Frame design with grade beam is optional.)

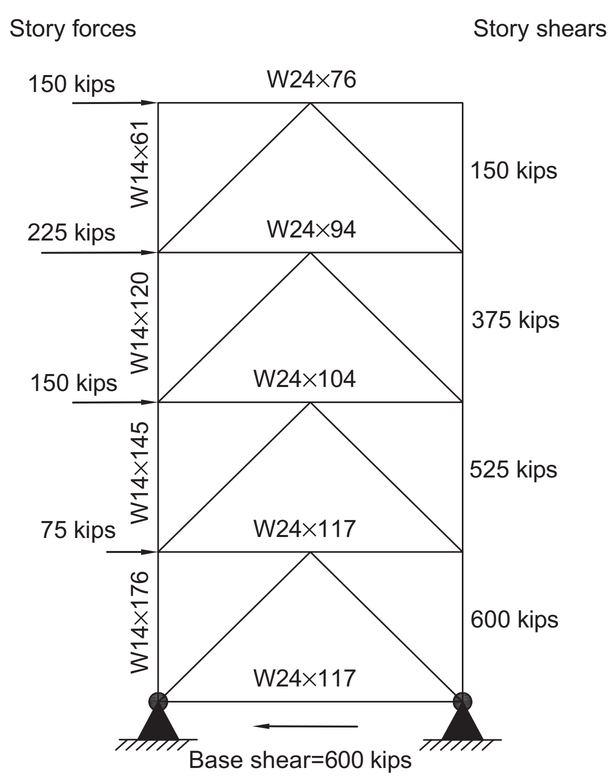

Fig. 5. Four-story braced-moment frame.

Table 1. Four-Story Frame Data												
Story	V_s (kips)	P_b (kips)	P_y (kips)	P_b/P_y	k_2	k_1	M_u (kip-in.)	V_m (kips)	V_m/V_s	V_t (kips)	V_t/V_s	Beam
4	150	75	1120	0.062	0.97	1.15	10000	124	0.83	26	0.17	W24×76
3	375	188	1385	0.125	0.94	1.15	12700	165	0.44	210	0.56	W24×94
2	525	263	1535	0.158	0.92	1.15	14450	170	0.32	355	0.68	W24×104
1	600	300	1720	0.161	0.92	1.15	17658	206	0.34	394	0.66	W24×117
0	600				1.00	1.15	16350					W24×117

Table 2. Four-Story Frame with Modified Beam Design Data												
Story	V_s (kips)	P_b (kips)	P_y (kips)	P_b/P_y	k_2	k_1	M_u (kip-in.)	V_m (kips)	V_m/V_s	V_t (kips)	V_t/V_s	Beam
4	150	75	1120	0.067	0.97	1.15	10000	124	0.83	26	0.17	W24×76
3	375	188	1120	0.167	0.92	1.15	10000	116	0.31	255	0.69	W24×76
2	525	263	1120	0.234	0.88	1.15	10000	112	0.21	413	0.78	W24×76
1	600	300	1120	0.267	0.86	1.15	10000	110	0.18	490	0.81	W24×76
0	600				1.00	1.15	10000					W24×76

Solution:

The frame is analyzed as shown in Tables 1 and 2.

where

M_u = beam plastic moment

P_b = beam axial load

P_y = beam axial yield load

V_m = story moment frame shear

= $2M_u k_1 k_2/h$

V_s = story shear

V_t = story brace frame shear

h = story height

= 180 in.

For k_1 and k_2, refer to the Appendix or Richard et al. (2024), and the AISC *Specification* (2016a).

For this frame design, the story braces resist 17%, 56%, 68%, and 66% of the story shear forces. If all the beams are replaced with more flexible W24×76 beams, the story brace forces are 17%, 69%, 78%, and 81% of the story shear forces, as shown in Table 2.

For comparison, The UFM rationale assigns all the story shear to the braces so that the ratio V_t/V_s would be equal to 1.00 for all stories.

Table 3. Beam Designs for the Four-Story Frame

Story	V_s (kips)	$0.5V_s$ (kips)	M_u (kip-in.)	$Z_{req'd}$ (in.^{3})	Beam Selected	Z Beam (in.^{3})	P_b (kips)	P_y (kips)	P_b/P_y	k_2	k_2k_1	
4	150	75	6750	135	W24×55	134	37.5	810	0.046	0.98	1.13	ok
3	375	187	16830	336	W24×117	327	93.5	1720	0.054	0.98	1.13	ok
2	525	262	23580	472	W24×146	418	131	2150	0.061	0.96	1.10	ok
1	600	300	27000	540	W24×176	511	150	2585	0.058	0.97	1.11	ok
0	600	300	27000	540	W24×176	511	150	2585	0.058	0.97	1.11	ok

REDESIGN OF MULTISTORY BRACED-MOMENT FRAMES

Using the braced-moment frame in Figure 5, redesign this frame so that the braces and moment frame each resist approximately 50% of the story shears. In the iterative design procedure for the redesign, make the following approximations for all stories: estimate $k_1 = 1.15$ and $k_1k_2 = 1.0$ so that the beams meet both strength (k_2) and stiffness (k_1) requirements. Specify an acceptable design criterion for k_1k_2. Estimate the plastic moment in the beam.

$$M_u = h_x V_m / 2 \tag{6}$$

where h is the story height and V_m is moment frame shear. Compute the beam plastic modulus required to select the beams for redesign.

$$Z_{req'd} = M_u / F_y \tag{7}$$

Shown in Table 3 are the selected beam designs using this rationale and where a selected design criterion $k_1k_2 \leq 1.15$ is satisfied for all the selected beams.

With the schedule of beams shown in Table 3, the moment frames resist approximately 50% of the story shears. Design the braces to resist 50% of the story shear. With this schedule of beams, the potentially large shear forces in the beams in the connection region of chevron-braced frames are reduced by approximately 50% (Sabelli and Bolin, 2021, 2022). The design rationale shown here results in a significant reduction in the forces and weights of the frame braces by including the moment resistance of the frame. When frames are designed using loads determined herein, the dual system provisions of SEI/ASCE 7 should be satisfied.

SUMMARY

A chevron frame analysis and design rationale for multistory buckling restrained braced frames that includes the inherent moment frame forces when the frame is subjected to seismic or wind forces that result in inelastic frame displacements is presented herein. The evaluation of the distribution of the story shears between the braces and the moment frame is made using conventional plastic analysis of the moment frame. This rationale includes the moment frame action and may be used to optimize story shear distributions between the frame braces and the moment frame as shown in the design example. The design methodology of AISC Design Guide 29 (Muir and Thornton, 2014) wherein all the story shear is resisted by the braces is applicable for elastic frame response.

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APPENDIX

Derivation of k_1

Figure A-1 depicts a magnified view of the plastic hinge rotation. The offset hinge rotation, θ_h, is calculated as:

$$\begin{aligned}\theta_h &= \theta + \frac{2\theta L_h}{L - 2L_h} \\ &= \theta\left(1 + \frac{2L_h}{L - 2L_h}\right) \\ &= \theta k_1\end{aligned}$$

where L_h is the hinge offset and L is the length of the beam. k_1 is then determined as:

$$\begin{aligned}k_1 &= 1 + \frac{2L_h}{L - 2L_h} \\ &= \frac{L}{L - 2L_h}\end{aligned}$$

Derivation of k_2

The beam plastic moment, M_p, is evaluated using the beam-column interaction equations given in AISC *Specification* Section H1 (2016a). Assuming the beams (with gross area, A_b, and strong axis plastic modulus, Z_b) are in uniaxial bending, the moment capacity for a given axial load, P, is found by rearranging the equations as shown:

$$k_2 = \frac{M_p}{M_u} = \begin{cases} \dfrac{9}{8}\left(1 - \dfrac{P}{P_y}\right) & \text{for } \dfrac{P}{P_y} \geq 0.2 \\ 1 - \dfrac{P}{2P_y} & \text{for } \dfrac{P}{P_y} < 0.2 \end{cases}$$

where

$$P_y = F_y A_b \text{ and } M_u = F_y Z_x$$

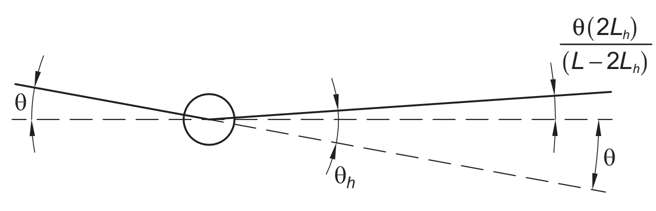

Fig. A-1. Magnified view of plastic hinge rotation.