DEFLECTION AMPLIFICATION FACTORS FOR DUCTILE BRACED FRAMES

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ABSTRACT :

For most seismic braced frames, strength rather than stiffness governs design. Still, it is important for designers to understand braced frame drift and predict inelastic deformations under severe earthquakes. Often in practice, inelastic drifts are estimated by amplifying the elastic drifts that occur under an equivalent lateral force. In current U.S. provisions, displacement amplification factors are about half of the strength reduction factors. Results from time history analyses of 36 braced frames under a suite of 10 earthquakes are used to investigate the accuracy of current methods to estimate inelastic drifts. Buckling restrained braced frames (BRBFs), special concentric braced frames (SCBFs), and eccentrically braced frames (EBFs) are considered. An alternative method of estimating inelastic drifts is investigated where only the shear components of the elastic drift are amplified.

KEYWORDS: **BRBF, C_d, DAF, Drift, EBF, SCBF**

1. INTRODUCTION

Steel braced frames are subject to large inelastic deformations under severe earthquake loading. During building design roof drift and interstory drifts are usually estimated. Being able to estimate maximum deflection (Δ_{max}) is important for many reasons: (1) estimating minimum building separation to avoid pounding; (2) estimating maximum story drifts; (3) checking deformation capacity of critical structural members; (4) checking P-delta effects; and (5) detailing connections for nonstructural components (Uang and Maarouf, 1994). Under current U.S. provisions inelastic drifts can be estimated by scaling up elastic deformations from the equivalent lateral force (ELF) with an amplification factor. Currently the deflection amplification factor (DAF), referred to as C_d in NEHRP documents (FEMA 2003), is a constant based only on the frame type used in the building. NEHRP provisions list C_d as: 5½ for buckling restrained braced frames (BRBF), 5 for special concentric braced frames (SCBF), and 4 for eccentrically braced frames (EBF).

Historically, estimated drifts have included both frame flexural drift, and frame shear drift. Flexural drift is defined as the drift that occurs in stories because of axial deformations in columns in stories below. Flexural drifts accumulate moving up a frame. The portion of drift that remains after flexural drift is subtracted from total drift, is defined as shear drift. Interstory shear drifts do not accumulated from story to story. While total roof drift is important for pounding, most structural and non-structural damage is a function of the interstory shear drifts.

In this paper, the accuracy of U.S. C_d factors for braced frames is investigated and a possible alternate method of estimating inelastic drift is explored. This method considers scaling only the shear component of elastic story drifts. More accurate scaling methods would allow the engineer to improve safety and reduce costs without running complex models.

2. METHODS

Thirty-six strength controlled buildings were designed for the study. There were three building types: BRBF, SCBF, and EBF. Within each building type three heights (3-, 9-, and 18-story) and four strength levels were represented. Building plan dimensions and floor masses matched those used in the SAC moment frame study (Gupta and Krawinkler, 1999). Seismic weights, W, for the 3-, 9-, and 18- story buildings were 31.8, 97.3, and 108 MN (1790, 5470, and 6040 kips). Braced bays were located around the perimeter of the buildings. SCBFs had braces in the two-story-X configuration (Figure 1) to reflect practice that avoids V bracing because of unbalanced vertical loads that must be resisted by the beams after brace buckling (AISC 2005). The same brace configuration was used for BRBFs (Figure 1) while the EBF buildings, identical in plan, had chevron bracing. The 18-story buildings were 72.8m (239 ft) tall, just below the 73.2m (240 ft) maximum height allowed for braced frames (Design Category D, ICC 2006).

Buildings were designed according to the 2006 IBC (ICC, 2006) equivalent lateral force procedure and AISC Seismic Provisions (2005). A Los Angeles, California, site was used for design with S_{DS}=1.11 and S_{D1}=0.61, where S_{DS} and S_{D1} are the site design spectral accelerations at 0.2 and 1.0 seconds in terms of gravity. S_{DS} and S_{D1} are based on the MCE × 2/3. The importance factor was taken as 1. The equivalent lateral forces for the 3-, 9-, and 18- story buildings were 0.134W, 0.056W, and 0.0342W. To investigate the influence of strength, four frames were designed at each height, each with different demand/capacity ratios for the ductile elements (braces or links). See Prinz (2007) for member sizes in each frame. D/C ratios that are close to but less than 1.0 represent buildings that would normally be designed and built. For the shorter SCBFs, brace sizes were governed by slenderness or width-thickness requirements, so none have D/C near 1.0.

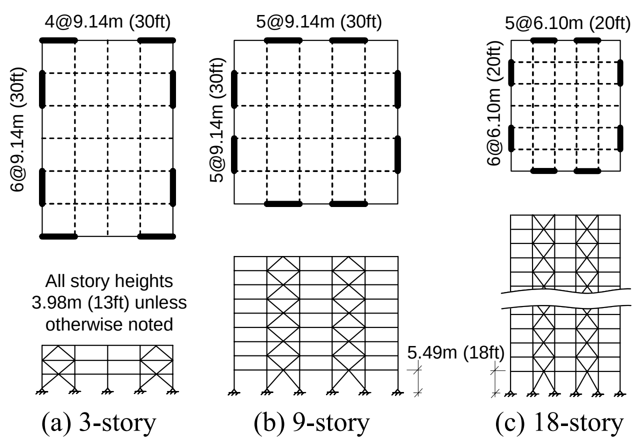

Figure 1 Plan and elevation views of SCBF and BRBF buildings
(EBF buildings similar but with chevron bracing)

Each frame was analyzed with both dynamic time history analysis (THA) and static analysis under the equivalent lateral force (ELF). ELF analysis was performed using Risa-2D (RISA Technologies, 2005). THA analysis was performed using Ruaumoko (Carr, 2006). Dynamic analyses were performed using suites of ten earthquake records, primarily from California events. Earthquake records were scaled so that the mean spectral acceleration of the suite for a range of building periods was greater than the design spectra over the same range. Compared to period-independent scaling procedures, this method of scaling has been shown to result in reduced scatter of response data (Kurama and Farrow 2003). Different suites were used for the analysis of the 3- and 9-story, and 18- story frames so that scaling factors greater than three were not required. Specific information on earthquake records and scaling factors can be found in Richards (2008).

DAFs were back-calculated by taking the roof or story drift from the time history analysis and dividing by the corresponding value from the ELF analysis. THA values were taken as the average for the ten ground motions used in the study. DAF values for roof drift and interstory drifts were calculated for each frame. In addition to calculating total interstory drifts for each frame, shear only interstory drifts were also calculated by subtracting out the flexural components of drift.

3. DRIFT AMPLIFICATION FACTORS

Results from the analysis showed that the back-calculated DAFs varied depending on the type of drift being studied as well as frame type, building strength, and building height. Because the back-calculated DAFs varied so greatly, roof drifts and interstory drifts have been treated separately by frame type.

3.1. Roof Drift

Roof drift is defined as the lateral deflection of the building at the roof divided by the height of the building. Back-calculated DAFs showed significant trends, especially when plotted by frame type and building height as shown in Figure 2.

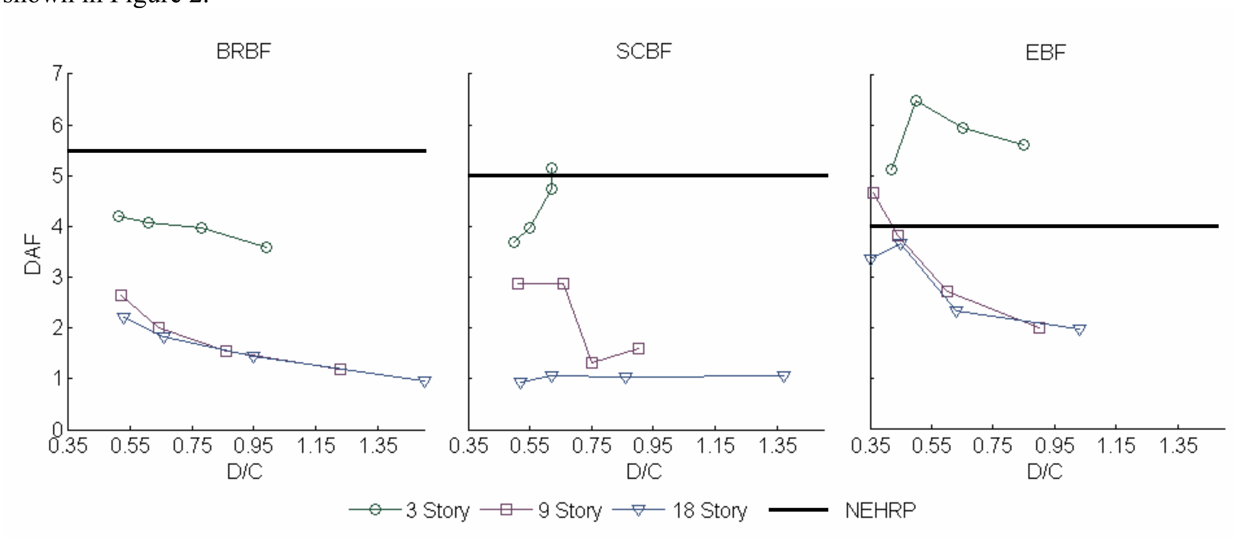

Figure 2 Roof Drift DAFs

When looking at roof drifts BRBFs provided the most predictable behavior while SCBFs provided the least. C_d factors provided in NEHRP (bold lines in Figure 2) were overly conservative in all cases except 3 story EBFs . In the taller 9- and 18-story frames DAF values seem to be largely independent of frame height and strength. NEHRP recommended DAF values for tall buildings were, for the most part, 2 to 4 times the values calculated from the analysis. Interestingly, 9- and 18- story frames with D/C values near to 1.0, had similar DAFs regardless of building type. For taller buildings with D/C ratios near 1, using a constant value of 2 for all frame types may more reasonably predict roof drift than current NEHRP values. Shorter frames universally had significantly higher DAF values near, and in the case of the EBF, exceeding, NEHRP recommended values.

3.2. Interstory total drift

Data showing DAF calculated using total story drifts (flexural plus shear) according to equation 3.1 is shown in Figure 3. In order to improve readability of the data some of the frames have been omitted. Two frames of each system and height have been shown and the corresponding D/C ratio displayed on the plot.

$$\text{DAF}=(\text{Total Story Drift THA})/(\text{Total Story Drift ELF}) \qquad (3.1)$$

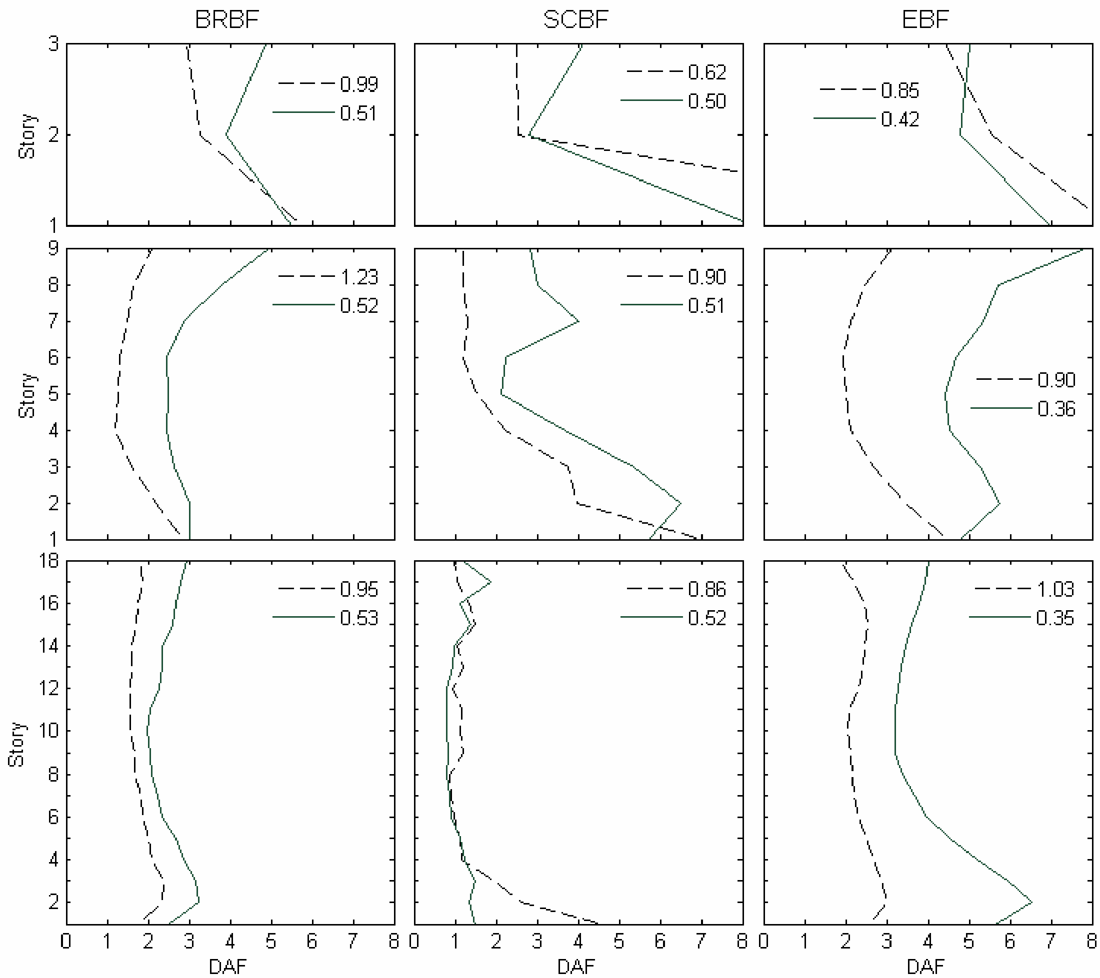

Figure 3 Total Interstory Drift by Floor

DAF values for BRBFs did not vary greatly by floor and decreased as the height of the frame being analyzed increased. The NEHRP recommended value of 5½ is showed to be reasonable for the three story frames, while a lower value of 3 would be more appropriate for the 9- and 18-story frames.

Three and 9-story SCBF frames DAF values varied greatly by floor and these heights of SCBFs routinely had DAF values that exceeded the NEHRP recommended value. The 18-story SCBF frames, on the other hand, had very low and uniform DAF values, except for in the bottom three stories.

EBF frames had higher DAF values than BRBFs for all building heights. Frames with low D/C ratios exceeded the NEHRP recommended value in all cases studied. Taller 9- and 18- story EBF frames with D/C values near 1 had DAF values that were lower than the recommended value, and for the 18-story would be represented better by a value of 3.

3.3. Interstory shear drift

Figure 4 shows the results for shear only DAF as calculated using equation 3.2.

$$\text{DAF=(Shear Story Drift THA)/(Shear Story Drift ELF)} \qquad (3.2)$$

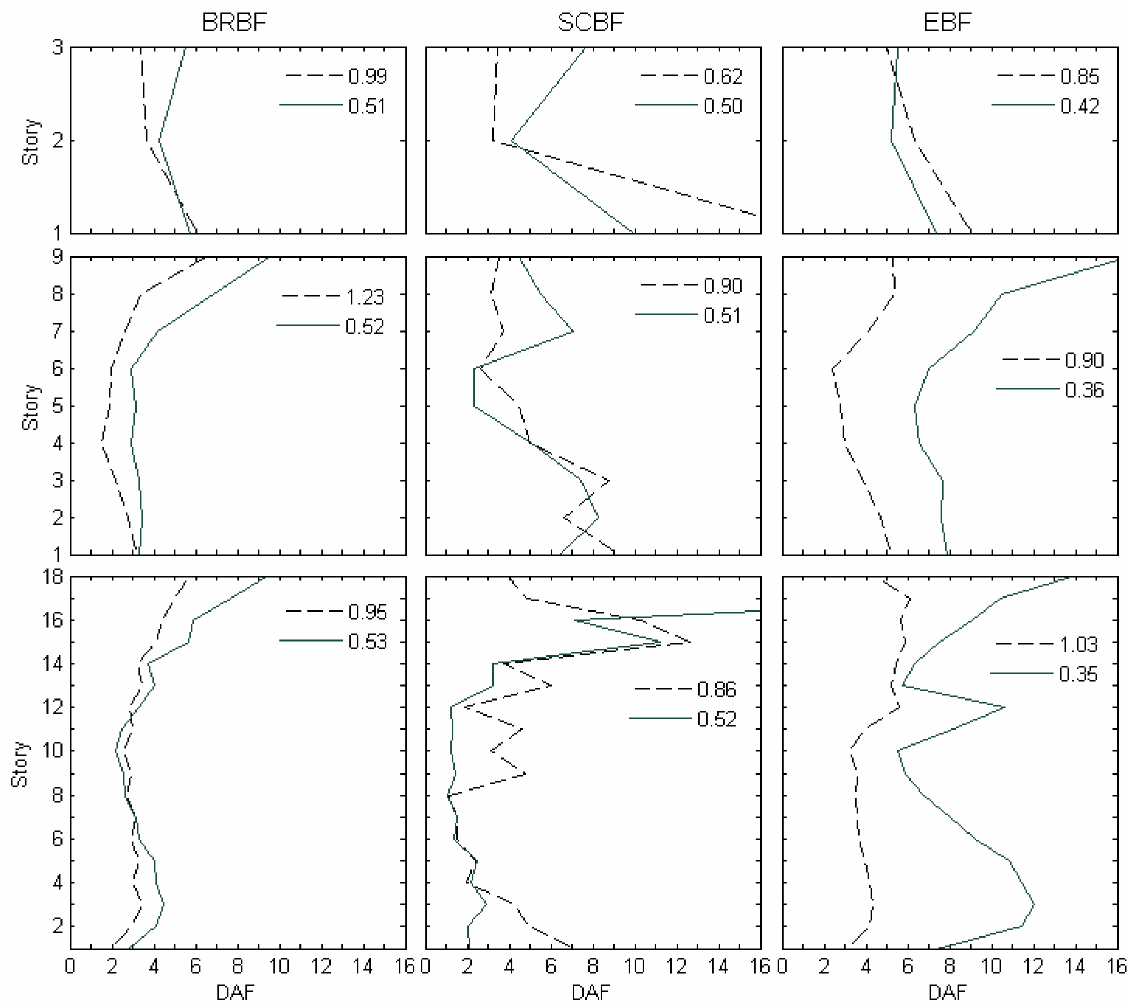

Figure 4 Shear Interstory Drift by Floor

Like the total interstory drift by floor plot, Figure 4 also shows only two frames per plot to facilitate readability. It should be noted that the plots in Figure 4 are not to the same scale as the plots in Figure 3 due to higher values. Shear only interstory drift DAF values were consistently higher, and varied more by floor than did total interstory drift DAF values. BRBF frames continued to have the most consistant DAF values over the height of the building, with SCBF frames continuing to have the least. Because the data provided by looking only at the shear component of drift consistently contains a high amount of variability by floor and strength level, significant conclusions on alternate DAF values are hard to attain.

4. CONCLUSIONS

While it is understood that the number of frames looked at in this study is small (36), and that more research should be done before any alternate methods should be taken into practice, certain trends are notable.

Roof drift DAFs varied greatly in most cases from the NEHRP recommended values. Looking at D/C ratios near 1, tall buildings (9- and 18-story) could use a constant DAF of 2 for all frame types and achieve greatly improved accuracy in predicting roof drift. One notable issue of concern is that the 3-story EBF frames DAF values were higher than the NEHRP recommended value and would be better served by a DAF of 5½ or 6.

Improved prediction of damage to be expected in both structural and non structural components may be possible by looking at interstory drift caused by only the shear components, but the usefulness of this method may be hampered by the unpredictable and erratic nature of shear only data and relationships.

It may be just as effective to get better calibrated factors for amplifying total drifts. These factors could take into account: building height, D/C ratio, frame type, and the type of drift being analyzed. Many cases show that they might well be served by utilizing lower constant values for interstory DAF such as 3 for 18-story BRBFs and EBFs, or 2 for 18-story SCBFs. The only case for interstory drift where the NEHRP recommended values seemed to be reasonable was for the 3-story BRBFs.

NEHRP recommended DAF values for BRBFs and EBFs are 5½ and 4 respectively. Results of the study consistently showed that back-calculated DAF values for EBFs were actually higher than those from BRBFs, and some increase in accuracy could be obtained simply by switching these two values.

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