Seismic Response of BRBFs Coupled With Heavy Gravity Columns

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SUMMARY:
Buckling restrained braced frames (BRBFs) have become a popular lateral force resisting system in the United States. In order to control residual drifts in BRBFs, moment frames may be included to create a dual system. In most BRBFs, gravity columns have insignificant lateral stiffness and play a minimal roll in the seismic response. This paper explores dual systems with BRBFs that operate in parallel with heavy gravity columns, rather than full moment resisting frames. Such systems may be more economical because they do not require special moment resisting connections, and more efficient because all of the columns in the building participate meaningfully in the lateral response in all directions of loading. The redundancy of the system is reminiscent of more traditional seismic design, where all components are involved in the response. An analytical study was conducted to determine the distribution of strength and stiffness between BRBs and heavy columns that results in the best economy and performance.

Keywords: braced frames, dual systems, response history analysis, structures, residual drift

1. INTRODUCTION

In typical U.S. practice, a few bays in a steel building will be used for the lateral-force-resisting system. The rest of the steel framing will contribute little to the seismic response because it has little or no lateral stiffness relative to the lateral-force-resisting bays. For example, consider the building shown in plan below [Figure 1(a)] with four braced bays in each direction. The heavy-lined elements indicate those that will resist lateral forces in the left-right direction. A model of one quarter of the building might looks something like [Figure 1(b)], where the associated gravity columns are represented by a single column. Since the gravity columns have no lateral stiffness by themselves they provide minimal post-yield stiffness after braces yield and lose their stiffness [Figure 1(c)].

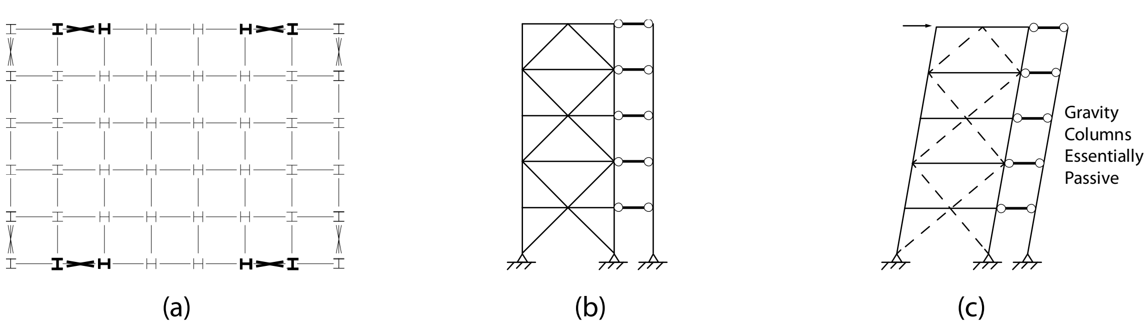


Figure 1. Typical braced frame building: (a) plan view indicating lateral-force-resisting bays; (b) 2-D model that might be used for response history analysis; (c) gravity columns have minimal contribution to the inelastic response

Sometimes dual systems are employed to achieve better seismic performance. Dual systems often consist of braced frames with secondary moment frames that provide stiffness after the braces yield. Dual systems are expensive in the U.S. because of labour costs for special moment connections. Figure 2 illustrates the building of Figure 1, with secondary moment frames added. As before, the remaining gravity columns are essentially passive, so only a fraction of the steel members [elements indicated with heavy lines in Figure 2(a)] are resisting lateral forces in the left-right direction.

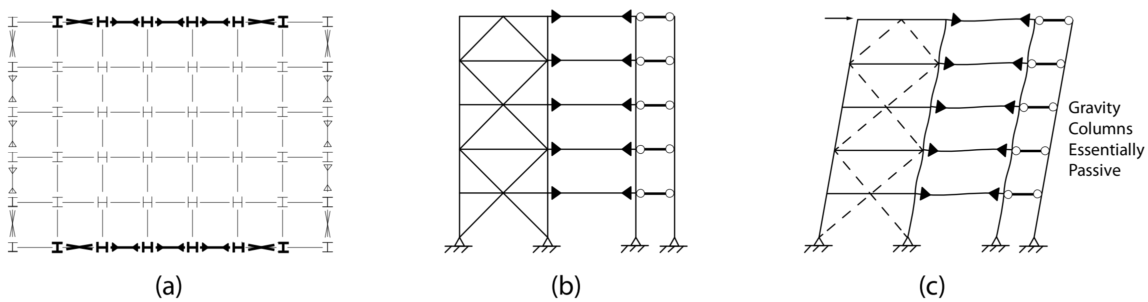


Figure 2. Dual system version of Figure 1 building: (a) plan view indicating lateral force resisting bays; (b) 2-D model that might be used for response history analysis; (c) gravity columns have minimal contribution to the inelastic response

This paper explores the performance of systems where all the columns in a steel building are active in resisting lateral forces [Figure 3(a)]. This is accomplished by providing large braces in at least one story [Figure 3(b)], such that the story remains essentially elastic under severe earthquake loading [Figure 3(c)]. This story constraint allows all the gravity columns to function as cantilevered columns (cantilevered from the stiff story) [Figure 3(c)]. It will be shown that these cantilevered gravity columns can be designed to remain elastic during severe earthquake loading and provide post-yield stiffness. The gravity columns will have much less stiffness than the primary system, but their combined stiffness is significant after the braces yield. This approach may offer similar-or-better performance than moment-frame dual systems [Figure 2] at dramatically lower cost since no additional moment connections are required and the existing steel in all the gravity columns is being used for lateral resistance in both directions.

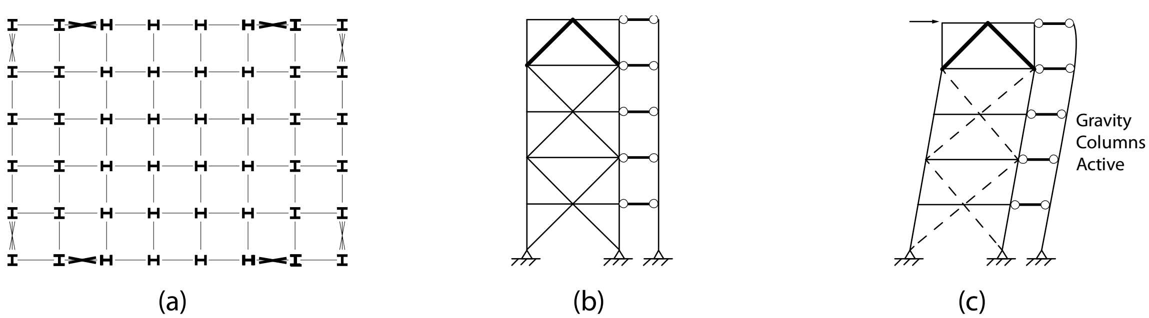


Figure 3. Proposed system to be explored: (a) plan view indicating that all vertical elements are part of the lateral force resisting system; (b) 2-D model that might be used for response history analysis; (c) gravity columns are active in the response because of constraint at one or more stories

This concept, of providing a stiff story (or stories) to activate gravity columns, could be employed with any steel system. In this paper, buckling-restrained braced frames (BRBFs) will be used to demonstrate the concept since BRBFs are becoming increasingly popular and have been shown to have somewhat greater residual drifts than other ductile steel systems. However, the principles are equally relevant to special concentrically braced frames (SCBFs), eccentrically braced frames (EBFs), and special moment resisting frames (SMRFs).

2. BACKGROUND LITERATURE

Excessive residual drifts in buildings are unacceptable because they are a safety hazard and may be expensive or impractical to repair. It has been found that residual drifts greater than 0.5% cause building occupants to experience nausea and headaches (McCormick, Aburano et al. 2008). High residual drifts lead to expensive repair cost or total loss of a building (Erochko, Christopoulos et al. 2011). As such, it is important to understand what influences the amount of residual drift that a building will have and how it can be mitigated.

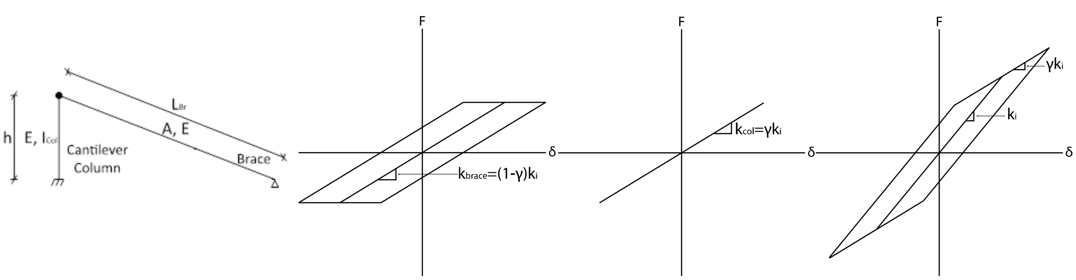
Two of the most common steel lateral force resisting systems for buildings in high seismic regions in the U.S., buckling restrained brace frames (BRBFs) and moment resisting frames (MRFs), are known to have high residual drifts. Research has shown that both of these systems are susceptible to residual drifts that may result in costly repairs or replacement (Sabelli, Mahin et al. 2003; Choi, Erochko et al. 2008; Tremblay, Lacerte et al. 2008; Erochko, Christopoulos et al. 2011).

The residual drift in a building is sensitive to the post-yield stiffness of the building. Buildings with higher post-yield stiffness will have lower residual drifts than buildings with low or negative post-yield stiffness (Macrae and Kawashima 1997; Borzi, Calvi et al. 2001). Traditional systems can be modified to have higher post-yield stiffness through the use of dual systems, which combine a primary system such as a BRBF with an elastic secondary system such as a moment frame. Adding an elastic moment frame as a secondary system has been found to reduce the residual drift in buildings (Kiggins and Uang 2006; Qiang 2008; Maley, Sullivan et al. 2010). However, the moment connections for these frames can be expensive.

3. SDOF PARAMETER STUDY

To quantify how gravity columns might be more effective in reducing residual drift, single and multiple degree of freedom models were studied using response history analysis. This section describes the single degree-of-freedom (SDOF) parameter study.

The SDOF system consisted of an elastic cantilever column and an elasto- plastic brace that met at a node [Figure 4(a)]. The column was 3.96 m tall and the brace was 9.96 m long. A mass of 184x10^3 kg was assigned to the top node. The hysteretic behaviour of the system was a combination of the brace and column. The system was analysed using OpenSees with the column modelled with an elasticBeamColumn element and the brace modelled as a corotTruss element.



(a) (b) (c) (d)

Figure 4. SDOF model: (a) geometry; (b) hysteretic behaviour of brace only; (c) hysteretic behaviour of column only; (d) combined hysteretic behaviour

The initial stiffness, k_i, of the system is equal to the sum of the brace stiffness, k_{brace}, and the column stiffness, k_{col}. After the system yields, the stiffness is just the stiffness of the column, k_{col} , which is expressed in terms of the initial stiffness as γk_i [Figure 4(d)].

For this study, k_i and γ were varied over a wide range. For each pair, the system yield strength was back-calculated based on the brace area and column moment of inertia required to achieve k_i and γ, thus the systems represented the strength-stiffness relationship of braced frames with elastic cantilever columns. Systems were analysed with each combination of k_i and γ under a suite of ten earthquakes. The earthquakes used in the study are the same as used in (Richards 2009) and are all California events (Figure 5).

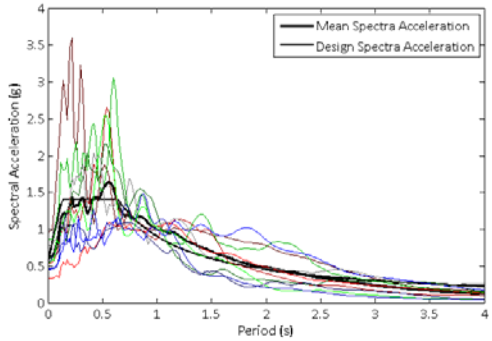


Figure 5. The response spectra for the earthquakes and the design spectra

After the systems were analysed under the suite of earthquakes, the maximum and residual drifts were output. The maximum drifts were averaged over the suite of earthquakes and plotted verses the period to create spectra [Figure 6(a)]. The residual drifts were likewise averaged and plotted [Figure 6(b)].

The systems with the highest post-yield stiffness (γ = 0.99) had essentially no residual drift, while the systems with very low post-yield stiffness (γ = 0.01) had high residual drifts. The greatest decreases in residual drift cames when the post-yield stiffness was increased from 1% to about 5-10%; further increase of the post-yield stiffness resulted in diminishing returns [Figure 6(b)].

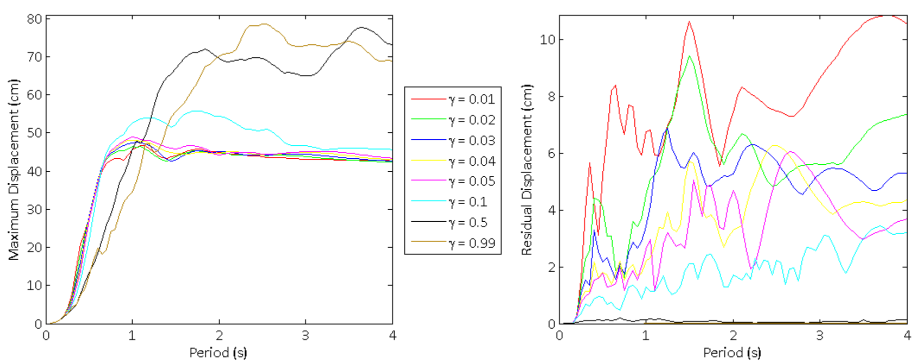


Figure 6. Results from SDOF parameter study: (a) maximum displacement; (b) residual displacement

These results are consistent with previous SDOF studies (Pettinga, Christopoulos et al. 2007). Pettinga et al. recommend designing the secondary lateral force resisting system such that the post-yield stiffness is between 5 and 10%, arguing that further increase in post-yield stiffness would not significantly decrease the residual drift.

4. FIVE-STORY BUILDING CASE STUDY

A five story BRBF was designed and analysed to demonstrate the effectiveness of BRBFs with gravity columns used as a secondary system, providing about 5% post-yield stiffness.

4.1. Baseline Design and Model

The building was designed according to the Equivalent Lateral Force (ELF) procedure from ASCE 7-10 (ASCE 2010). The five story building was assumed to be located at a site with a short period acceleration (S_{DS}) of 1.4g, a one second acceleration (S_{D1}) of 0.9g, and site class D soil. The building area is 3500 m^2 per floor with a seismic weight of 4.0kPa per floor (Figure 7). The same column sizes were reasonable for both the gravity columns and lateral frames (see Table 1). The brace sizes for the braced frames are given in Table 1.

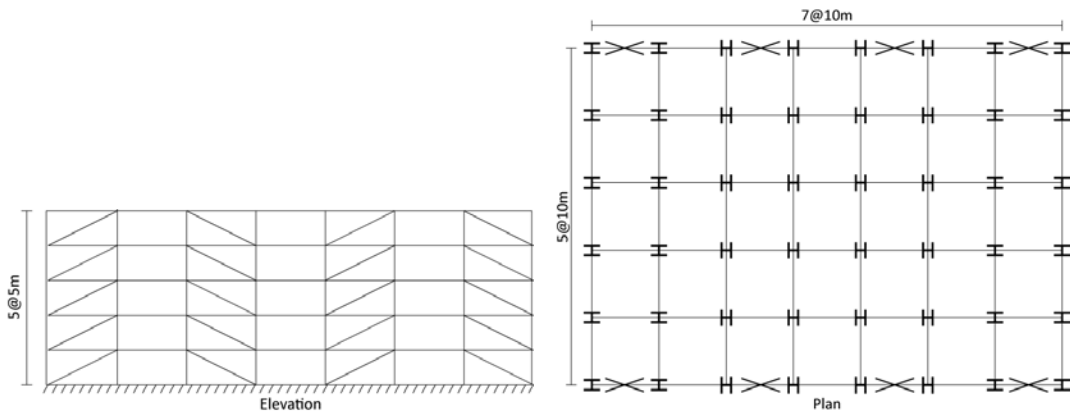


Figure 7. Five story building: (a) elevation view; (b) plan view

Table 1. Column and Brace Sizes for Five-Story Frame

Story	1	2	3	4	5
Column	W12x79	W12x79	W12x53	W12x53	W12x53
Brace Size (cm^2)	35.5	32.3	25.8	22.6	12.9

A model was developed that represented one-eighth of the building [similar conceptually to Figure 1(b)]. It consisted of a single 2-D braced frame with a column that represented four associated gravity columns, two oriented for strong axis bending, and two oriented for weak axis bending. The model was analyzed under the same suite of ground motions as used in the SDOF study. Maximum and residual drifts are shown for the model in Figure 8. This model, which represents the ELF design is referred to as the baseline model.

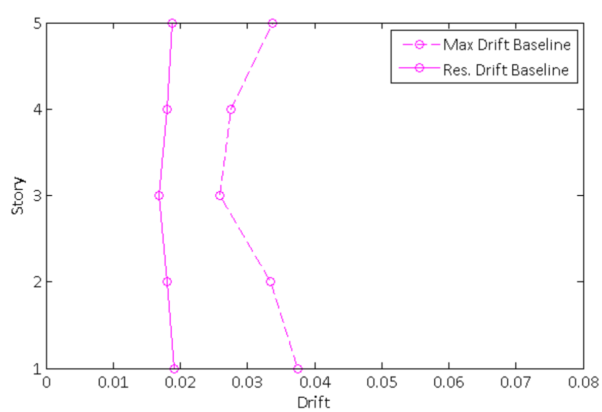


Figure 8. Maximum and residual drifts for baseline BRBF model

4.2. Variations that Use Gravity Columns as Secondary Lateral System

Three variations of the baseline model were generated that had modifications intended to activate the lateral stiffness of the gravity column (that represented four gravity columns in the building associated with the frame). For the first variation of the baseline model, the gravity column had a fixed connection to the ground. The second and third variations activated the lateral stiffness of the gravity column by having a strong brace that remained essentially elastic in either the top story or the middle story [similar in concept to Figure 3(c)]. The three variations were analysed with four different column sizes to quantify how increasing the column size would further help to decrease the residual drift. The four different column designs resulted in a combined gravity column moment of inertia approximately 1, 2, 3 and 4 times the original (see Table 1 for original sizes).

For the fixed gravity column variation the reduction in residual drift depended on the size of the gravity column (Figure 9). When the original-sized gravity column was used, the residual drift decreased by half for the first story, but increased in the top two stories (comparing residual drift for I=1.0 and residual drift for the baseline case in Figure 9). However, top story residual drifts did get smaller than the baseline drifts as the size of the gravity column was increased; the upper stories experienced the largest decrease in residual drift. The residual drifts became more uniform when the column stiffness was increased. Maximum drifts (dashed lines) actually increased in the upper stories and decreased in the lower stories as compared to the baseline case. In practice, it would be difficult to fix all of the gravity columns so this variation is primarily for reference.

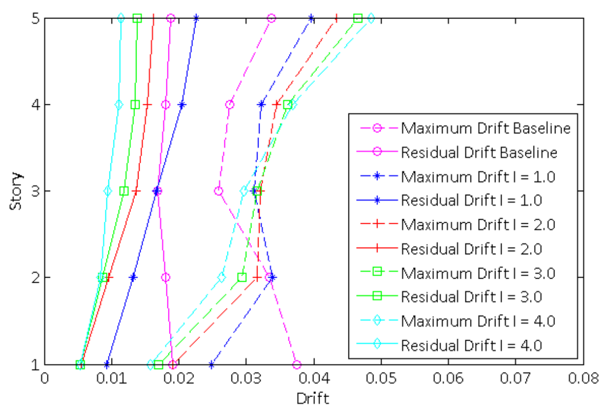


Figure 9. Maximum and residual drifts for the configuration with fixed gravity columns

The second variation had a heavy brace in the top story [similar to the concept in Figure 3(b)]. For this variation, the brace size at the top story was three times the size of the bottom brace. The heavy brace in the top story remained essentially elastic during earthquake loading, resulting in no residual drifts at that level and the residual drifts at the lower stories were lower than the baseline drifts (Figure 10). Further, as the column stiffness was increased, the residual drift at the lower stories continued to decrease. The maximum drifts for this configuration remained lower than the maximum drifts for the baseline configuration with the exception of the third story where the maximum drifts were slightly higher. These results indicate that simply increasing the top-story brace size in braced frames, even without changing column sizes, may dramatically reduce residual drifts in the upper stories.

Another analysis was done on the same configuration, but with the brace areas reduced by 50% in the lower four stories. Decreasing the brace sizes actually lowered the residual drifts [results in Figure 11]. For double-sized gravity column (I=2), the residual drifts were decreased to half of the baseline drift at the lower levels and even more at the upper levels. As the column size was increased further, the drift at the lower stories decreased even more. The results from this variation suggest it is a promising option for mitigating excessive residual drifts in BRBFs.

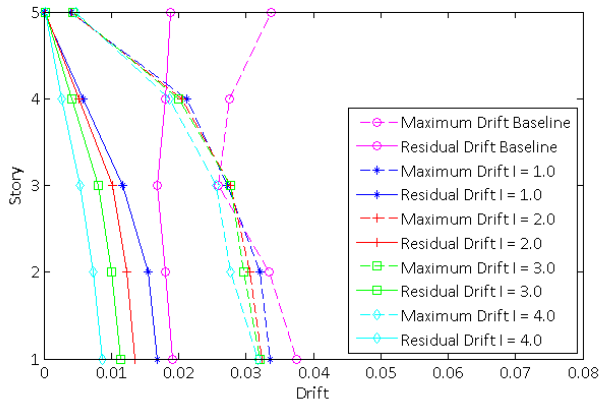


Figure 10. Maximum and residual drifts for the variation with heavy top brace

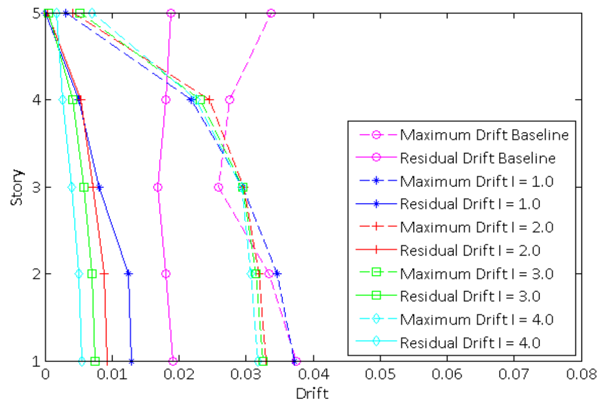


Figure 11. Maximum and residual drifts for the variation with heavy top brace and brace sizes reduced by 50%.

The third variation had a heavy brace in the third story. For the case with the normal-sized gravity column, the brace in the third story did behave elastically and the residual drifts were greatly reduced (Figure 12). The drifts were concentrated in the bottom two stories for this configuration. The drifts for these stories were higher than the other drifts, but still lower than the baseline model. For the upper stories, the residual drifts were small due to the displacement being constrained at the third story. As the column size increased, the heavy middle brace did not stay elastic and the residual drifts did not decrease as much.

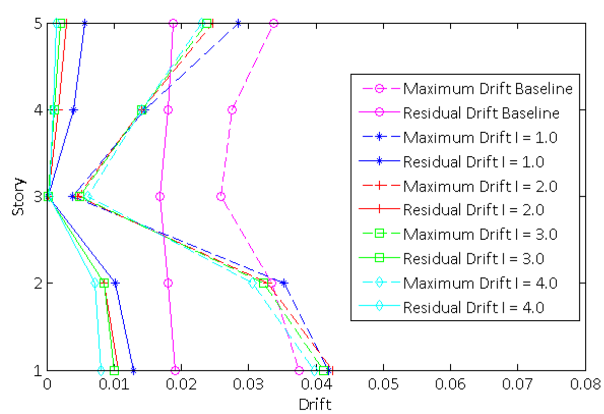


Figure 12. Maximum and residual drifts for the variation with a heavy brace at the third floor

5. CONCLUSIONS

The SDOF study and five-story building case study presented herein suggest that gravity columns might be employed more effectively in mitigating residual drifts in steel frames. By providing a stiff story that remains essentially elastic, gravity columns become cantilevered columns that can provide post-yield stiffness.

In the five story case study, residual drifts were halved at the first story by: 1) providing a strong brace in the top story, 2) reducing other brace sizes by half, and 3) doubling column sizes. This mitigation approach would likely be less expensive that incorporating a special moment resisting frame as a dual system.

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