Performance of Structural Members
In Seismic Retrofitted Frames with Viscous Dampers

J.K. Whittle, M.S. Williams & A. Blakeborough
University of Oxford, UK

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SUMMARY:
Seismic retrofit with supplemental viscous dampers may be employed to improve building performance; however, the added damping may be counter-productive if the supporting structural members cannot sustain the damper reaction forces. This paper addresses a practical design issue of supplemental damping, the capacity of the structural system to accommodate large levels of damping and associated increased damper reaction forces. Five brace-damper arrangements within a steel MRF with uniform damping were investigated under two design-basis earthquakes with nonlinear time history analysis. It was found that linear viscous dampers can contribute critical axial forces to the supporting system, regardless of the out-of-phase trait of viscous damper forces. Brace-damper arrangements with diagonals and multiple brace-damper sets per floor were the most effective means of distributing the axial damper forces and protecting the lower-storey columns from overstressing.

Keywords: dampers, moment resisting steel frame, seismic design, column capacity

1. INTRODUCTION

Strategic placement of supplemental damping aims to improve building performance under seismic or wind events. However, supplemental damping is counter-productive if the supporting structural members cannot sustain the damper reaction forces during an earthquake. Although the damper reaction forces of a fluid viscous damper are ideally out of phase with the peak frame forces (displacement and acceleration being out of phase with velocity), there remains a need to check the capacity of the structural members in the interim phase between peak displacement (maximum member forces) and zero displacement (maximum damper forces). In this phase, the damper reaction forces contribute an axial load on the columns, additive to the gravity loads. Therefore, the lower storey columns become critical members collecting the axial force of the supported columns and dampers.

Some studies of supplementally damped buildings avoid this capacity check by relying on the advantageous out-of-phase relationship between linear viscous dampers and the structural system. Nonetheless, a practical design issue with supplemental damping is the capacity of the structural system to accommodate large levels of damping and associated increased damper reaction forces (Hanson and Soong 2001). Interestingly, seismic retrofits with linear fluid viscous dampers (FVDs) have shown an increase in the axial loading and sometimes overstressing of columns after added damping. This paper addresses the practical issue of structural member capacities with added supplemental dampers. A brief background reviews the influence of axial forces due to dampers and introduces brace-damper arrangements. The impact of the damper reaction forces are assessed with a capacity check of the final stressed state of the structural members with added dampers. While controlling the vertical damping distribution, multiple brace-damper arrangements are explored to improve the load path of the damper reaction forces and reduce the axial load on the columns.

2. BACKGROUND

A review of the effect of dampers on column axial loading and the influence of brace-damper arrangements is presented in this section. Damping distribution will refer to the vertical distribution of total damping per floor, while brace-damper arrangements refer to the horizontal distribution of damping in terms of bay location per floor.

2.1. Axial Loading of the Columns

Supplemental devices in an MRF contribute damper reaction forces to the frame, particularly the axial force that must be resisted and transmitted through the columns (Constantinou and Symans 1993a). The last step of the performance-based supplemental design procedure (Kim and Choi 2006) is checking that the structural members can resist the axial and shear forces from the supplemental dampers. Investigations of damping distributions for ten- and twenty-storey steel MRFs with linear viscous dampers installed diagonally within interior bays showed an increase in column axial force for all damping distributions as well as a redistribution of member forces to columns connected to the dampers (Kim and Choi 2006). In all cases, greater than 20% effective damping was added in the form of viscous dampers. Constantinou and Symans (1993b) experimentally showed the out-of-phase behaviour of a linear fluid viscous damper and based on the results, claimed that column compression failure is not a critical concern with added linear FVDs. In contrast, a retrofit of a three-storey, pre-Northridge, steel MRF building with linear FVDs (at a 40% effective damping ratio) caused substantial increases in column axial forces and base shear, which would require re-strengthening of the base columns (Uriz and Whittaker 2001). Although the maximum force of the linear FVD is out of phase with the structure's peak drift, the forces are additive during the interim phase between peak drift and peak velocity and may overstress the columns, regardless of the out-of-phase damper and structure relationship.

2.2. Brace-Damper Arrangements

Since brace-damper arrangements control the load path of the damper reaction forces, they may be used to re-route axial forces and reduce the axial loads on critical columns. Although a conventional approach is to restrict the brace-damper set to only interior or exterior columns, Apostolakis and Dargush (2010) found that for friction dampers and buckling-restrained braces installed in steel MRFs, a combination of interior and exterior columns produced the best structural performance (Fig. 1). Mezzi (2010) suggests conventional and innovative bracing arrangements for energy-dissipating braces for an 18-storey reinforced-concrete frame (Fig. 2). Two energy-dissipating braces per floor were used in the numerical analysis and were constrained in terms of yield force per floor for each brace arrangement (Mezzi 2010). Decreased column bending moments occurred in the arrangement of braces directly connected (such as IN, XD, and SP). The SP brace arrangement produced the smallest axial forces of the non-random arrangements (Mezzi 2010).

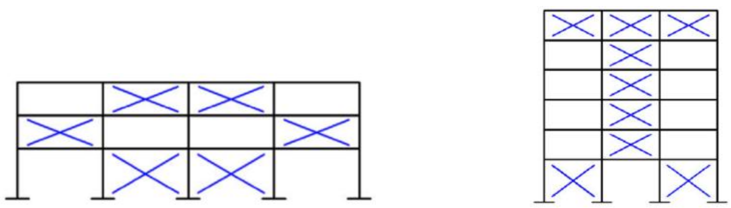

Figure 1. Optimal Arrangements of Friction Dampers and Braces (left) and BRBs (right) (Apostolakis and Dargush 2010)

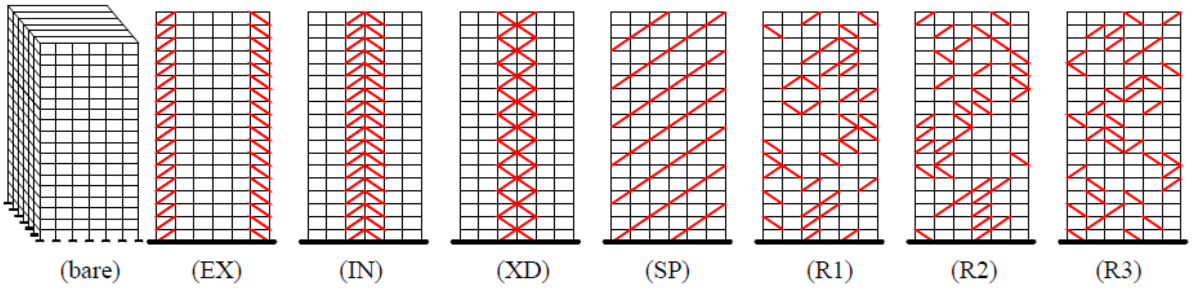

Figure 2. Tested Bracing Arrangements of the Perimeter Concrete Frame (Mezzi 2010)

3. METHODOLOGY

The methodology describes the damper retrofit scenario, a description of the five brace-damper arrangements, selected ground motions, time history analyses, and the demand/capacity check of structural members.

3.1. Damper Retrofit Scenarios and Brace-damper Arrangements

A retrofit scenario of a regular steel moment-resisting frame building with uniform damping under two design-based earthquakes (DBE) was selected (Whittle et al. 2012). This frame employs a damper typology of chevron braces with horizontally placed, linear viscous dampers. The pinned braces transfer the damper reaction forces to the columns and were designed as artificial braces with low-mass, high-stiffness, and further design and capacity checks of the braces are beyond the scope of this research.

Five brace-damper arrangements were created with different damper force load paths (Fig. 3). Some resemble common arrangements or architectural constraints, such as restriction of brace-dampers to either interior or exterior bays (A1 and A5), while A2, A3, and A4 connect brace-damper columns at adjoining floors with a combination of exterior and interior bays. This concept showed promise in Apostolakis and Dargush (2010) and Mezzi (2010). The motivation for selecting A2, A3, and A4 is their potential to counteract the axial compressive force from the damper at one column with the tensile force from another damper at an adjoining floor, thereby reducing the axial loads on the interior columns. Fig. 4 is a simplification of the load path of the damper reaction forces, considering only the damper forces' axial components on the columns. If all the axial reaction forces from dampers were equivalent, then each brace-damper arrangement could be assessed by the number of unbalanced axial forces collected in the base columns. For example, for A4 in Fig. 4, many of the interior column axial loads from dampers would be counteracted due to the brace-damper arrangement, resulting in one unbalanced axial load in each interior column and three unbalanced damper axial forces collected and resisted by the exterior base columns. However, while the column axial loads from the dampers may be similar at adjoining floors, the damper reaction forces will vary depending on the interstorey velocity at the installation floor, leaving a residual axial force even with force counteraction.

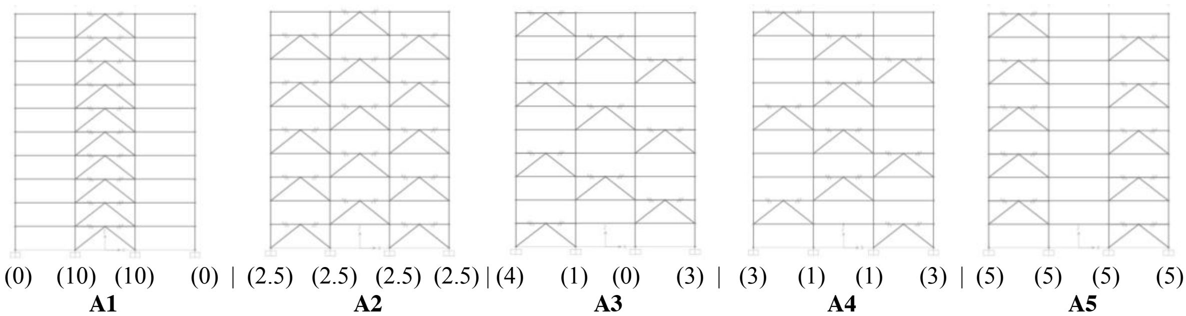

Figure 3. Brace-damper Arrangements

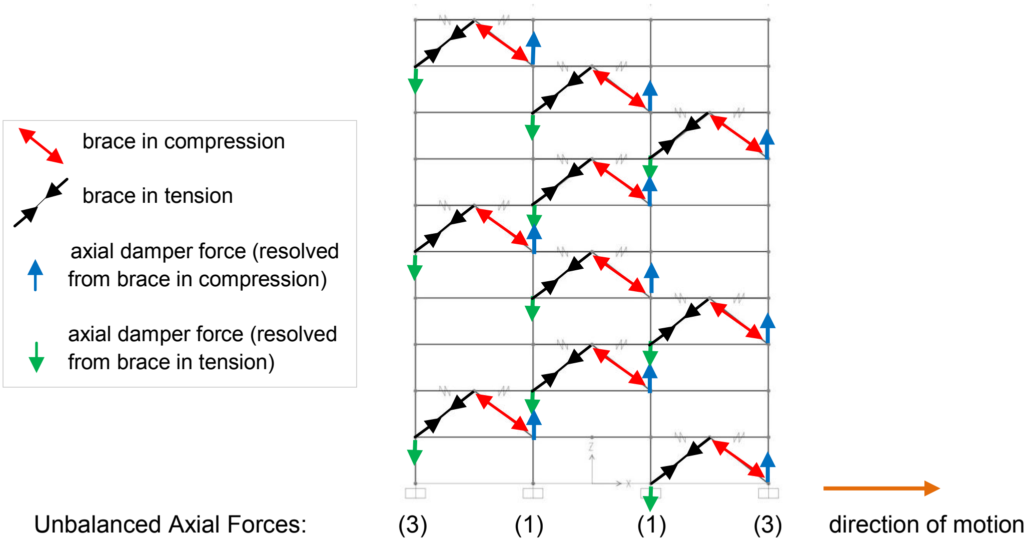

Figure 4. Axial Force Counteraction –Unbalanced Damper Reaction Axial Forces for A4

Descriptions of the arrangements and the associated load paths of the damper axial forces are presented in Table 1. The assumption of a rigid floor diaphragm eliminates the potential of unsymmetrical brace-damper placement prompting y-axis rotations and torsion. Finally, a uniform damping distribution (81.2 kN-sec/cm per floor, Whittle et al. 2012) is constrained in each brace-damper arrangement.

Table 1. Brace-damper Descriptions

Brace-damper Arrangement	Position	Objective	Load Path of Damper Reaction Axial Forces
A1	Central bay, original	Simplicity, keep dampers aligned and outer bays open	Interior columns resist damper reaction forces
A2	Triangular shape*	Distribute forces to interior and exterior columns	Interior dampers are twice the capacity of exterior dampers.
A3	Diagonals	Counteract interior damper forces	Similar to Mezzi (2010) SP pattern.
A4	Alternating diagonals	Counteract interior damper forces	Single unbalanced force in both interior columns and three unbalanced in exterior
A5	Outer bays	Architectural option of an open central bay	No force counteraction and five unbalanced damper forces

* Only arrangement including multiple brace-damper sets per floor.

3.2. Time History Analysis

Two ground motions were selected and scaled to the DBE (Whittle et al. 2012). The Imperial Valley 1979 ground motion (GM1) and the Manjil 1990 ground motion (GM4) represent average and low demands on the structure, respectively, based on the peak interstorey drifts of the uniformly damped building. The uniformly damped building experienced peak interstorey drifts of 1.01% under the Imperial Valley earthquake and 0.74% under the Manjil earthquake. Nonlinear time history analysis was performed using SAP2000 with each ground motion on the damped frame with various brace arrangements. The nonlinear time history with 0.01 sec time step was performed at the end of the nonlinear static load case, considering the static seismic load combination ($G + 0.3Q \pm E$) based on the full dead load G, partial live load Q, and earthquake load E.

3.3. Demand/Capacity Check of Structural Members

The SAP2000 steel member design tool (CSI 2009) was employed to check the final stressed state of the structural members with added brace-damper arrangements. The steel demand/capacity check is based on Eurocode 3, where the critical demand/capacity ratio for members is the bending-compression-buckling ratio (PMM) considering Euler and lateral-torsional buckling based on the interaction equations in EC3 6.3.3(4) (BS EN 2005).

The SAP2000 steel design check calculates the total axial demand/capacity ratio *PRatio* and major bending moment demand/capacity ratio *MMajRatio*, where both values are quotients of the applied force or moment and the design capacity of the member. The demand/capacity ratio (D/C) *PMM ratio* is the sum of the axial force demand/capacity ratio and the bending moment demand/capacity ratio. A PMM value greater than one will be used here to indicate overstressed members.

$$\text{PMM Ratio} = \text{PRatio} + \text{MMajRatio} \leq 1 \tag{3.1}$$

4. RESULTS AND DISCUSSION

The results of the brace-damper arrangements include an overview of the overstressed members for each configuration (total PMM ratio), individual demand/capacity ratios for axial forces and bending moments, and performance parameters, including drift and accelerations, of the structure with various brace-damper arrangements.

4.1. Overstressed Members

The column frame members of the interior MRF without dampers are shown in Fig. 5, including interior (I) and exterior (E) columns. Table 2 and Table 3 display the PMM D/C ratios for the ground and first floor columns under GM1 and ground floor columns under GM4. The ground floor columns are the only members to yield under GM4. A critical parameter is the maximum PMM ratio, which indicates the most stressed column in the system considering both flexural and axial capacity. Overstressed columns are shown in red. A lower maximum PMM ratio corresponds to a more desirable brace-damper arrangement.

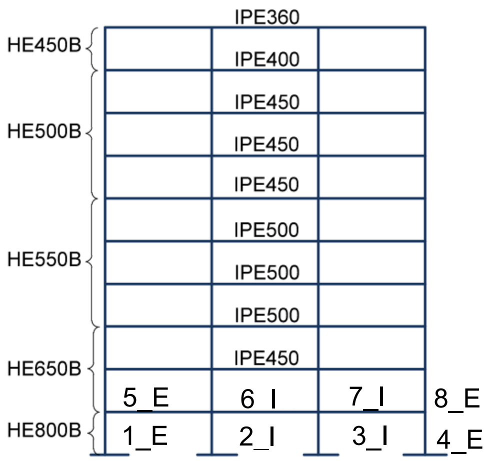

Figure 5. Column Frame Members

GM1 and GM4 produced PMM ratios similarly distributed amongst the five brace-damper arrangements. For example, arrangement 3 (A3) under both ground motions produces the lowest value of the maximum PMM ratios, a 22% reduction of the maximum PMM ratio compared to A1 under GM1 and a 20% reduction under GM4. Arrangement 2 and 4 (A2, A4) have similar performance under the respective ground motions, and arrangement 1 (A1) yields the largest PMM ratio under both ground motions. Arrangement 5 (A5) performs better than A1 but worse than A2, A3, and A4 under both ground motions. A3 is the only configuration under GM1 where the maximum PMM ratio occurs at an exterior column. A3 achieves a lower maximum PMM value by shifting the loads from the interior columns, which carry greater gravity loads, to the exterior columns. Standard deviation measures the disparity between column PMM ratios per floor. The arrangements most effective at minimising the maximum PMM ratio distribute the axial forces more uniformly to the columns, indicated by a lower standard deviation of the column PMM ratios per floor. This is the case under GM4, where similar standard deviations correspond with similar maximum PMM ratios for A2 and A4, and the minimum standard deviation corresponds to the lowest value for the maximum PMM ratio at A3. The correlation generally applies for GM1. This is not the case for the A5 ground floor columns, where A5 has the largest PMM ratio amongst A2, A3, A4, and A5, despite the second-lowest standard deviation under both ground motions.

Table 2. Overstressed Columns under GM 1 (Imperial Valley 1979)

Frame Members	Column Location (Floor/Bay)	Brace-Damper Arrangements PMM Ratios, Overstressed (PMM > 1)				
		(A1)	(A2)	(A3)	(A4)	(A5)
1_E	Ground Exterior	0.94	0.88	0.92	0.92	1.01
2_I	Ground Interior	1.28	1.08	1.07	1.08	1.34
3_I	Ground Interior	1.54	1.31	1.09	1.29	1.12
4_E	Ground Exterior	0.97	1.07	1.21	1.07	1.22
5_E	First Exterior	0.77	0.75	0.79	0.83	0.74
6_I	First Interior	1.11	0.88	0.83	0.91	1.02
7_I	First Interior	1.31	0.99	0.89	1.03	0.89
8_E	First Exterior	0.78	0.86	0.98	0.98	0.91
	Maximum PMM Ratio =	1.54	1.31	1.21	1.29	1.34
Std Dev (Ground Floor) =		0.28	0.18	0.12	0.15	0.14
Std Dev (1st Floor) =		0.26	0.10	0.08	0.09	0.12
Percent Reduction from A1: Max PMM =		-	15%	22%	16%	13%

Table 3. Overstressed Columns under GM 4 (Manjil 1990)

Frame Members	Column Location (Floor/Bay)	Brace-Damper Arrangements PMM Ratios, Overstressed (PMM > 1)				
		(A1)	(A2)	(A3)	(A4)	(A5)
1_E	Ground Exterior	0.71	0.68	0.70	0.71	0.75
2_I	Ground Interior	1.02	0.89	0.84	0.87	0.99
3_I	Ground Interior	1.05	0.94	0.84	0.94	0.93
4_E	Ground Exterior	0.76	0.75	0.77	0.76	0.79
	Maximum PMM Ratio =	1.05	0.94	0.84	0.94	0.99
Std Dev (1st Floor) =		0.18	0.12	0.07	0.11	0.11
Percent Reduction from A1: Max PMM =			10%	20%	10%	6%

4.2. Demand/Capacity Rations

Additional performance of the brace-damper arrangements may be acquired from the individual D/C ratios, including the total axial force ratio, the bending moment ratio, the axial force ratio from static loads, and the axial force ratio from added dampers. The total axial force ratio and bending moment ratios reflect the D/C ratios of the members after the static and ground motion time history load cases, while the axial load ratio from static loads (axial static force ratio) reflects the axial force ratio after the static load case only. The axial static force ratios are constant for each member size and location (e.g. an HE800B interior column) because the static loads were proportioned by tributary area.

The axial force ratio from added dampers (axial damper force ratio) neglects the contribution of the static gravity loads to the axial force ratio and emphasizes the relative size of the damper axial forces. Axial damper force ratios are presented as positive values, regardless of tensile or compressive direction. The axial damper force ratio $PRatio_{\text{added dampers}}$ is defined as the difference between the total axial force ratio PRatio and the axial static force ratio $PRatio_{\text{static}}$:

$$PRatio_{\text{added dampers}} = |\, PRatio - PRatio_{\text{static}} \,| \tag{4.1}$$

4.2.1. Ground Motion 1 – Overstressed Ground and 1st Floor Columns

Fig. 6 presents the D/C ratios for the regular building under GM1, with the ground floor HE800B members in the left column and the first floor HE650B members in the right column. Recall that the PMM ratio is equal to the sum of the total axial force ratio and the bending moment ratio.

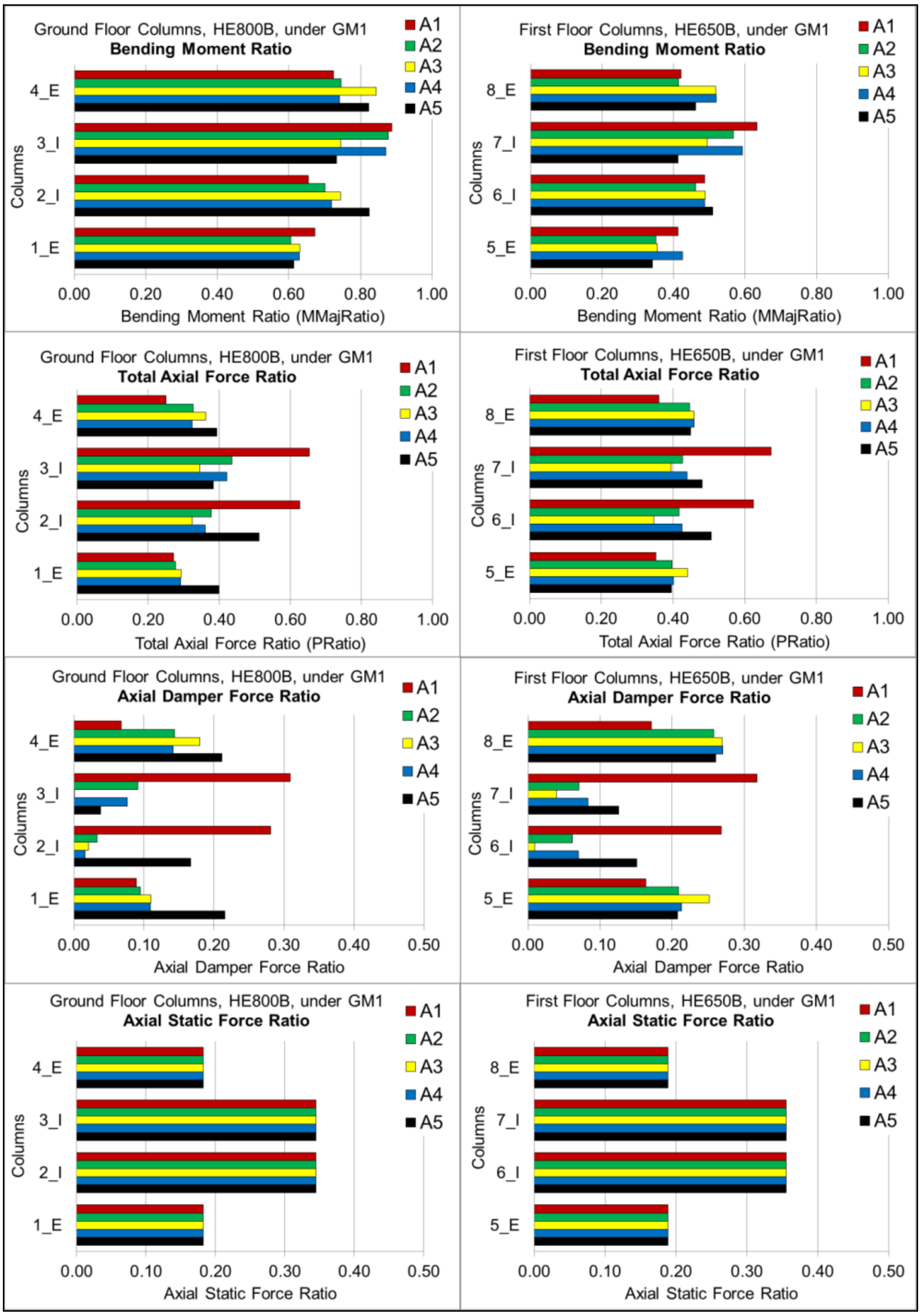

Figure 6. D/C Ratios under DBE GM1 – Columns at Ground (left) and First Floor (right)

For the ground floor columns under GM1, the bending moment ratio is a larger component of the PMM ratio than the total axial force ratio, with the exception of the A1 2_I column. First floor columns have more comparable bending moment and total axial force ratios, with variation depending on column location. The increase in axial force ratios from ground to first floor is likely attributed to the column size and capacity decreasing at the first floor without a similar decrease in axial force.

A comparison of the axial damper force ratio and axial static force ratio shows the merits of the force counteraction concept used in A2, A3, and A4. The interior column axial damper force ratios are much smaller than the axial static force ratios for A2, A3, and A4. The counteraction concept is particularly effective in interior columns of A3, where there is small to negligible axial damper force ratios, and also effective in A2 and A4, where small ratios exist in comparison to A1. In contrast, the axial damper force ratio in A1 is greater than or equal to 75% of the axial static force ratio at the interior columns at both floors. The axial damper force ratios at interior columns of A5 are also improved from the A1 interior columns, a result of distributing the damper reaction forces uniformly to exterior and interior columns. All arrangements except A1 have shifted the damper axial forces to the exterior columns, causing an increase in the axial damper force ratios at these columns compared to A1. Despite the fact that the brace-damper sets are restricted to interior columns in A1, exterior columns are still resisting a portion of the axial damper force.

4.2.2. Ground Motion 4 – Overstressed Ground Floor Columns
Fig. 7 includes the D/C ratios under GM4 for the ground floor HE800B columns. Similar to the GM1 results, bending moment ratios constitute a larger portion of the PMM ratios. Comparisons of the axial static force ratios and axial damper force ratios reveal the low contribution of the damper axial forces to the total axial force ratios for all brace-damper arrangements. Axial damper force ratios are at most 60% of the maximum axial static force ratio at exterior columns and 31% of the maximum axial static ratio at interior columns. A3 yields negligible axial damper force ratios at the interior columns and small contributions of axial force occur with A4, followed by A2 and A5. Note that the reduction in axial damper force ratio at interior columns results in larger exterior column axial force ratios, such that A1 and A5 are comparable in terms of maximum axial damper force ratio. Because GM4 is less-demanding than GM1, interstorey velocities and resulting damper reaction forces are smaller, prompting lower axial force ratios due to dampers.

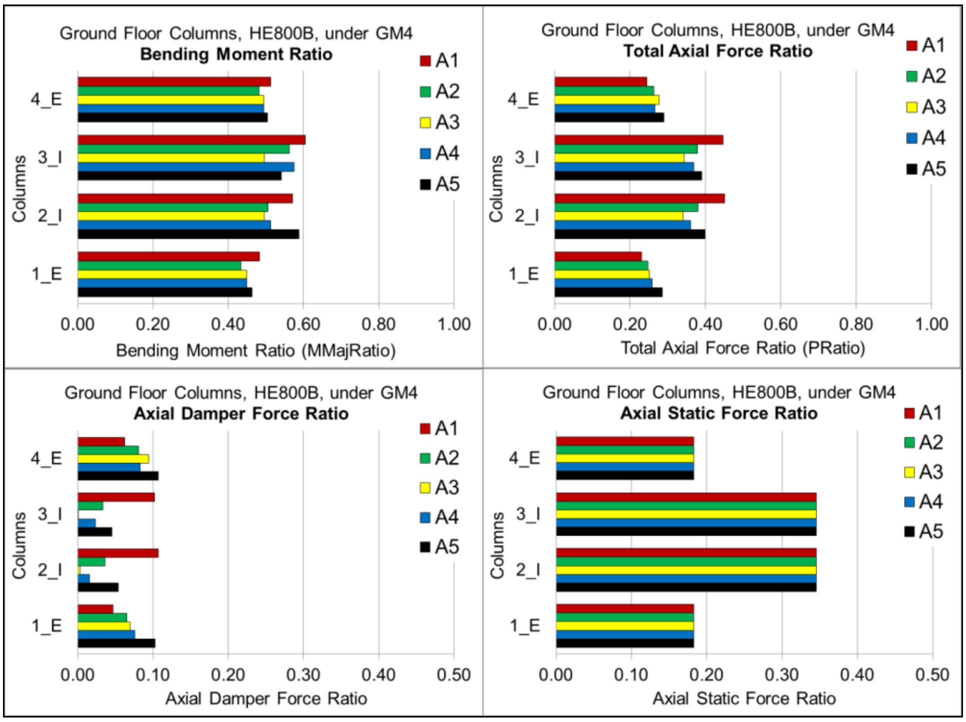

Figure 7. D/C Ratios under DBE GM4 – Ground Floor Columns

4.2.3. Discussion of Force Paths

The benefits of force counteraction and eliminating axial forces from dampers at the interior columns with A2, A3, and A4 are shown in the reduced axial force ratios from dampers at the interior columns under both ground motions. The level of reduction of axial force demand for various arrangements, in comparison to A1, depends on the seismic hazard level. A low-demanding ground motion (GM4) produced relatively small axial damper force ratios for all columns, at best (A2) a 24% reduction in the maximum axial damper force ratio and at worst (A5), the equivalent maximum axial damper force ratio, as compared to A1. A more demanding ground motion (producing peak drifts of 1%) prompted larger damper reaction forces and at best (A2 and A4) a 54% reduction in the maximum axial damper force ratio at the ground floor and at worst (A5) a 30% reduction in the maximum axial damper force ratio at the ground floor, as compared to A1.

In attempting to divert the axial forces from the internal columns, A5 shifted the load path prompting larger exterior column axial force demands and no improvement in maximum axial damper force ratio under GM4 but a 30% reduction in axial damper force ratio under GM1 at the ground floor as compared to A1. Despite superiority of A2 at reducing maximum axial damper force ratios under both ground motions, it did not reduce the moment demand on the interior members enough to best improve the overall maximum PMM ratios in the structure. The minimal axial damper force ratios at interior columns of A3 confirms that the force counteraction concept produces the expected results by reducing the unresolved forces on the interior columns and producing minimal axial forces from dampers. A3 achieves the lowest maximum PMM ratio in the ground and first floor columns.

4.3. Comparison of Performance Parameters

The structural performance of the system with various brace-damper arrangements was assessed in terms of peak interstorey drift and absolute accelerations. It is expected that each system will display equivalent structural performance because identical stiffness, mass, and damping properties were used per floor. The maximum performance parameters are summarised in Table 4.

Table 4. Maximum Performance Parameters for Brace-Damper Arrangements

Brace-Damper Arrangements	Max Peak Interstorey Drift (%)		Max Absolute Acceleration (m/sec^2)	
	GM1	GM4	GM1	GM4
A1	1.01%	0.74%	6.18	3.81
A2	1.00%	0.71%	6.17	3.74
A3	1.01%	0.72%	6.21	3.78
A4	1.01%	0.72%	6.21	3.78
A5	1.00%	0.74%	6.20	3.79

The maximum peak drift values are approximately equal under GM1 and similar under GM4 with the lowest value at A2 and largest drifts at A1 and A5. Maximum absolute accelerations are very similar for all arrangements, and best minimised by A2 under both ground motions. Marginal differences in interstorey drifts and accelerations amongst the five brace-damper arrangements are due to the horizontal damper locations per floor that prompt slight differences in the stressed state of the structural members. Residual drifts were negligible for all frame arrangements, which is confirmed by peak interstorey drifts and absence of hinge formation. Results show similar overall performance in terms of these performance parameters for all brace-damper configurations. Some improvement may be achieved with the triangular floor distribution of A2, where multiple dampers of lower force are introduced in comparison to arrangements with one brace-damper per floor.

5. CONCLUSIONS

An assessment of various brace-damper arrangements has shown that strategic placement of dampers horizontally per floor can be used as a design strategy to avoid overstressing structural members. Results of two ground motions and five frame arrangements suggest that linear fluid viscous dampers can contribute critical axial forces to the supporting system, regardless of the out-of-phase trait of viscous dampers. For example, the selection of the standard arrangement A1 under GM4 results in two overstressed ground columns, while strategic selection of any of the alternative arrangements (A2-A5) avoids overstressing the columns. However, the size of axial damper forces may be small in comparison to the axial static force depending on the ground motion demands. The influence of brace-damper arrangements on the structural member capacity may be greater when the structural members are approaching the demand/capacity limit (as seen with A1 under GM4 compared to A2-5), when there are large damper forces due to high seismic demands, and when there is a large quantity of viscous damping and therefore, increased damper reaction forces.

The review of the axial damper force ratios confirms the effectiveness of the force counteraction approach for arranging brace-dampers throughout a structure. Brace-damper arrangements may be used as a tool to control force paths and reduce axial force demands from dampers. The PMM ratios serve as the best assessment for the overall performance of the brace-damper system at reducing demands on structural members. The diagonal arrangement A3 provides the most effective damper reaction force path and best reduces the maximum PMM ratios, while the alternating diagonal A4 and triangular arrangements A2 are improvements over the single-bay arrangements of A1 and A5 in terms of best reducing maximum PMM ratios. Slightly enhanced building performance may be achieved with using multiple brace-damper sets per floor, as shown by A2. The interior bay A1 approach yields the highest demands on the interior columns and slightly decreased building performance compared to alternative arrangements. Therefore, restriction of brace-dampers to interior bays should be used with caution of overloading interior columns, as they are carrying a greater proportion of the axial static loads. In conclusion, the addition of viscous dampers requires that the structural capacity of the supporting members be checked, particularly to assess the axial damper force demands on the columns. Brace-damper arrangements with diagonals and multiple brace-damper sets per floor pose effective means of distributing the axial damper force and protecting the lower-storey columns from overstressing.

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