VISCOUS AND HYSTERETIC DAMPING – IMPACT OF CAPACITY DESIGN VIOLATION IN AUGMENTED STRUCTURAL SYSTEMS

Chloe C. Labise[1], Geoffrey W. Rodgers[1], Gregory A. MacRae[2] and J. Geoffrey Chase[1]

ABSTRACT

Capacity design, while protecting a structure against undesirable energy dissipations, has major implications on member sizes and overall cost. Furthermore, in some situations where protected elements possess some inelastic deformation capacity, it may be unwarranted. One of these situations is when the forces applied to the protected elements result from viscous dampers. This is because when viscous forces cause yielding in an element, the element deforms, so no deformation in the viscous damper is required. If no deformation is required, the velocity is zero, so there is no force. This implies that very little inelastic yielding is likely to occur in protected elements.

In order to investigate whether or not this is so, a single storey structure was designed and fitted with braces to reduce its response. Both hysteretic and viscous braces were used to obtain the same peak displacement response. The column strength was decreased by a fixed percentage and inelastic dynamic time history analysis was conducted. The amount of energy dissipated in the columns was then compared to determine whether hysteretic braces or viscous braces caused more column yielding so that appropriate over strength values could be developed for different brace types. It was found that the amount of energy absorbed by the column depends on the period but also on the brace design ductility. However, irrespective of the period or design ductility, the column hysteretic energy dissipated by a viscous brace was lower than that dissipated by a hysteretic brace. It follows that column yielding may be significantly less critical for viscous, rather than for hysteresis, braced structures.

Keywords: supplemental damping, earthquake engineering, structural design, inelastic deformation, viscous damping, hysteretic damping.

1.0 INTRODUCTION

Capacity design is an integral part of structural design techniques and well accepted within the structural design community. Under the strong-column, weak-beam design methodology it is assumed that the columns remain elastic during an earthquake response cycle, and that any inelastic response will be concentrated in the formation of a plastic hinge zone in the beam. However, in the case of structures with diagonal braces with either viscous or hysteretic dampers, the damping forces impose an additional axial load in the columns. These axial loads must be directly considered in design for completeness. If the additional axial loads in the columns due to the damping forces are neglected, axial column yielding may result, thus violating the capacity design approach goals and assumptions. However, this violation of capacity design may actually lead to a desirable outcome and is thus the primary focus of this investigation.

In structural design, a braced moment resisting frame can be considered a braced pinned frame with lateral stiffness provided only by the brace. Similarly, an un-braced moment resisting frame has rigid connections. These situations are shown schematically in Figure 1. Importantly, for augmented systems with added damping and/or stiffness elements to mitigate seismic or other environmental loads, the brace may also contain a viscous damper or some other form of hysteretic energy absorption. Such forms of augmented or additional energy absorption include sliding friction connections, specific added dissipation devices and, even more specifically, semi-active or active dissipation elements. All of these possibilities have been extensively studied and remain ongoing areas of significant investigation from retrofit solutions to next-generation structures.

---

[1] *Dept. of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand.*

[2] *Dept. of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand.*

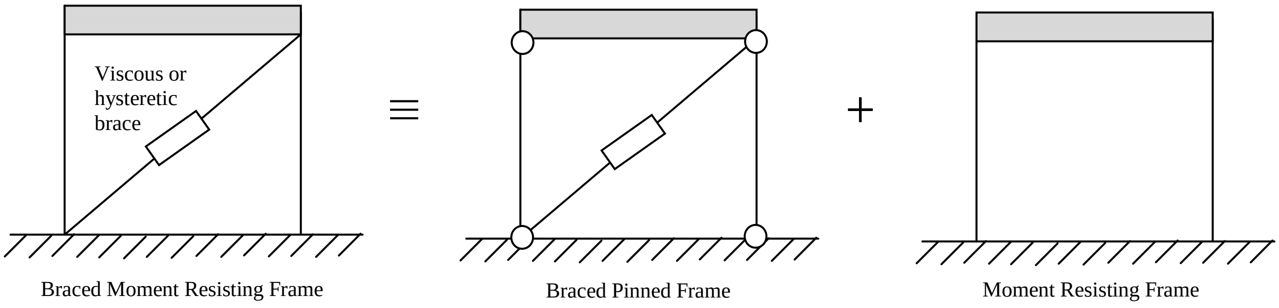

Figure 1: Schematic diagram of fundamental braced frame analysis approach.

The brace itself will likely have a linear force-displacement response, particularly if the analysis is related to design codes or spectral analyses. This response may be bilinear if it includes some form of yielding steel or device specifically designed to provide a bilinear response. For example, Figure 2 presents the overall response of a brace with a viscous damper, as well as the elements that contribute to that response for the overall frame system. In particular, the elliptical damper response assumes a sinusoidal displacement input. If the brace and frame are well matched, then the peak force in the overall response will be roughly equal to that of the structure itself, as seen in Figure 2. However, if the damper is mismatched to the frame, or if we get much bigger velocities, then a much less well-balanced response can result. Figure 3 shows a schematic representation of such a mismatched response.

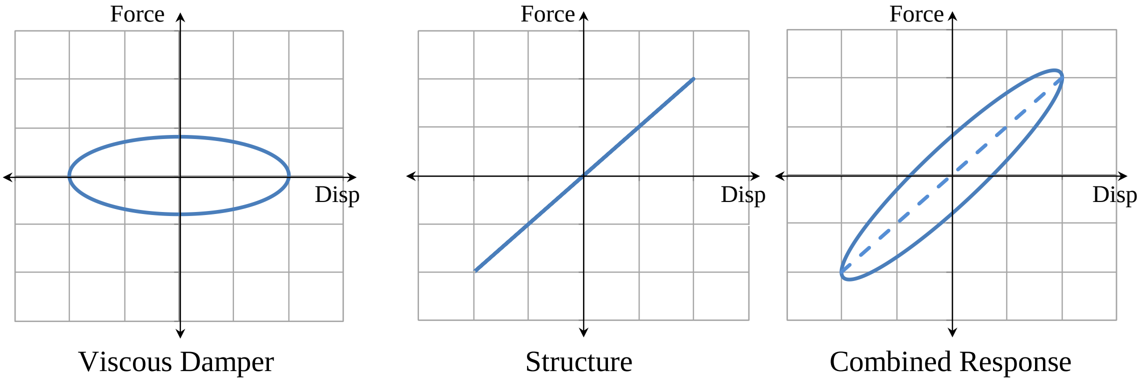

Figure 2:   Schematic diagram of brace displacement response with well-matched damper and frame.

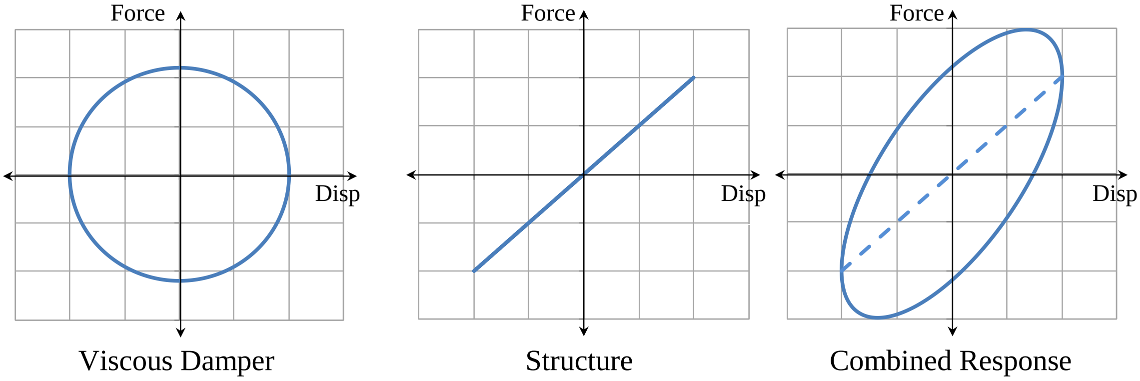

Figure 3:   Schematic diagram of brace displacement response with poorly-matched damper and frame system, or a system that was subject to much larger velocities than expected.

The importance of this phenomenon is that while an overall ‘well-balanced’ damping system can be implemented with careful design, it is difficult to control the earthquake response velocity of the structure. Therefore, it is difficult to predict the maximum force that will be present within a viscous damper. Consequently, as the damper force induces additional axial column force, it is difficult to predict the maximum force that will be present in the columns. Moreover, if the behaviour of the frame system is considered, it can be seen that if the column yields axially, then the diagonal member does not lengthen with further displacement, as seen in Figure 4. Equally, without yielding, large axial forces induce reductions in effective lateral stiffness, thus further affecting response. These observations, particularly considering when the column might yield axially, go against the typical analysis approaches employed with braced frame systems.

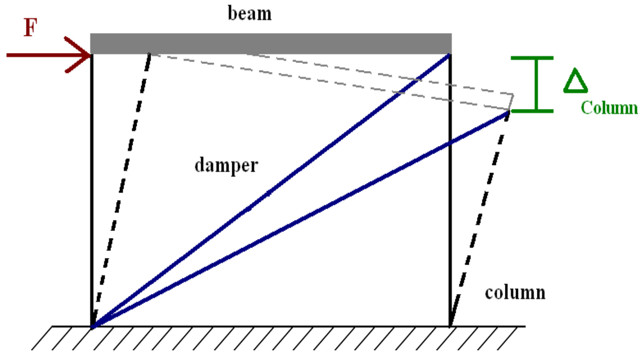

Figure 4: ***Schematic diagram of frame deflection, where axial column deflection results in no change in the length of the diagonal brace.***

This observation gives rise to the question: ***What if we made the columns just strong enough to resist the frame forces, and ignored the damper contributions?***

The conceptual advantage of this approach is that:

- ➢ if the column yields, the diagonal element will not change length with lateral frame deflection.
- ➢ therefore, the velocity within the viscous damper goes to zero.
- ➢ the force within the viscous damper goes to zero.
- ➢ the column will not yield, because there is no additional column force from the damper.
- ➢ for further displacements, forces are in the damper and there is no yielding.

➔ A very small amount of axial column yielding may mitigate high damping effects.

2.0 MODEL

2.1 Overall Model Information:

An elementary model is constructed using SeismoStruct v5.0.4. As shown in Figure 5, the model consists of four elements:

- 2 vertical columns,
- 1 main member (girder or floor slab),
- 1 elastic flexible truss brace or a bilinear truss brace or a damper.

Two concentrated mass elements are fixed on nodes 3 and 4 following a lumped mass model. Rectangular solid sections are used for the four elements. The columns and beam have a square section of 0.3 x 0.3 m and 0.1 x 0.1 m for the braces, which are arbitrary, but realistic, and used to demonstrate the overall concept.

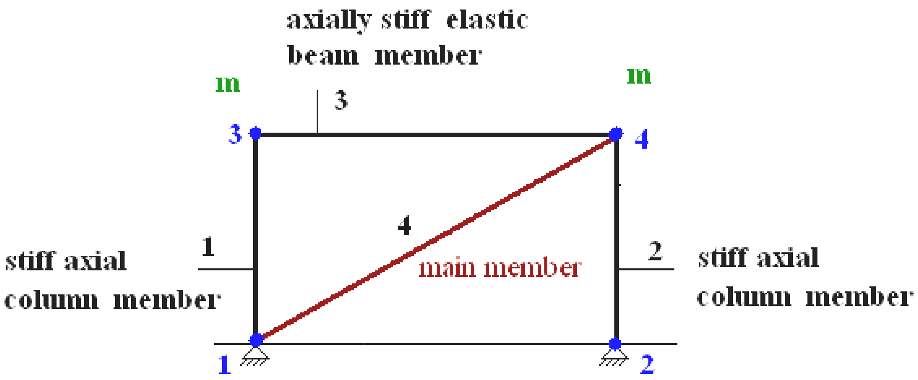

Figure 5: ***Schematic representation of the frame model. Joints are pinned for this braced frame configuration.***

2.2 Applied Loading:

The input ground motion for the analyses presented are the odd numbered records (N = 10) from the LA 10 in 50 records (Medium Suite) from the SAC Project suites of ground motions (Somerville, 1997), which are probabilistically scaled for probability of occurrence in the Los Angeles area. The resulting seismic loads are applied to nodes 1 and 2 in the horizontal direction. Rayleigh damping is applied to the simulations, with 5% inherent structural damping assumed for the structure. Table 1 details these input ground motions.

Table 1: Description of the earthquake records used for the analyses presented.

Record	Earthquake name	Peak ground acceleration (PGA) of the record (m/s²)
"la02"	Imperial Valley	6.6
"la04"	Imperial Valley, 1979, Array 5	4.8
"la06"	Imperial Valley, 1979, Array 6	2.3
"la08"	Landers Eqk, 1992	4.2
"la10"	Landers Eqk, 1992	3.5
"la12"	Loma Prieta, 1989, Gilroy	9.5
"la14"	Northridge, 1994	6.4
"la16"	Northridge, 1994	5.7
"la18"	Northridge, 1994, Sylmar	8.0
"la20"	North Palm Springs, 1986	9.7

3.0 METHODS

The following analyses are run. The overall approach considers elastic brace elements, a typical assumption, and bilinear yielding, inelastic braces. In addition, augmented damping systems are considered and further analyses are performed.

3.1 Elastic Truss Brace:

For the initial structure with an elastic truss brace, the period was determined to be 4.1s through an eigenvalue analysis. This value was determined using the values in Section 2.1 for the generic structure considered in this proof of concept analysis.

3.2 Bilinear Truss Brace:

Initially, the bilinear truss brace is implemented and an eigenvalue analysis is used to find the fundamental period (T_2 different from T_1 above) of this structure when it is linear elastic in response. A dynamic time-history analysis is then performed (with the previous structure) to look at the global response parameters. Several global response parameter results are examined. Specifically: 1) structural displacements, 2) forces and moments at the supports, 3) nodal velocities/accelerations, and 4) hysteretic force-displacement curves. The peak force in the brace (F_{brace}) is determined from the hysteresis curves. The yield strength of the brace is modified by dividing through by a lateral force reduction factor, *R*, to give a new brace yield strength, F_B, where:

$$F_B = \frac{F_{brace}}{R} \quad \text{where } R \text{ is a coefficient} \geq 1.0 \qquad (1)$$

The dynamic time-history analysis is then re-run and the peak displacement of the node 4 ($d_{\max}$) and the peak force in the column (F_{column}) are determined. The yield strength of the column is modified to F_C where:

$$F_C = F_{column} * \alpha \qquad (2)$$

where α is the fraction by which the column is under-strength, and takes a value between 0 and 1 (excluded). Thus, α is defined as the ratio: (*Column_strength / Column_strength*$_{elastic}$). For a range of values of *R* and α it is possible to plot the hysteretic curve of the brace and use the hysteretic curve of the column to calculate the cumulative inelastic column displacement. In particular, this range of values allows one to determine how the yield load affects response relative to a (fixed) brace element and thus the impact on response as it varies.

3.3 Damper Truss Brace:

In this analysis, a dashpot is added to the structure with an elastic truss brace. The dynamic time-history analysis is run and damping values of the dashpot are changed to find the same peak displacement of node 4 ($d_{\max}$) that is equal to that for the structure with the bilinear truss brace. Once the peak displacement is matched, the yield force in the column is again modified by Equation (2) to study a range of effects and generalise the analysis.

Overall, for a range of *α,* the cumulative inelastic column displacement is calculated as an indication of the total amount of column yielding. Peak damper forces cannot be found directly in Seismostruct and were therefore calculated from other response variables.

4.0 RESULTS AND DISCUSSION

The analyses of a viscous brace structure are run with a range of different effective damping ratios. Figure 6 presents the structural response to the 'la02' earthquake from the SAC suite for the Imperial Valley ground motion. Figure 6a compares the response of a structure with no supplemental damping (ξ = 0%) to that of a structure with 20% effective damping (ξ = 20%). Figure 6b presents the comparison between the structure with no added damping (ξ = 0%) and the structure with viscous brace with 100% effective damping (ξ = 100%). It can be seen that the structure in Figure 6a has a good design balance and that while the peak force occurs at different displacements it is within 30% of the structure without supplemental damping.

However, in Figure 6b, the lateral displacement response is far less than that of the structure without the added damping, but the peak overall force is much higher. It is also important to note that the peak force, which occurs at the peak velocity, does not occur at the zero displacement position, which is what would be expected from a standard harmonic response. This result indicates that the peak velocity induced within the damper, and therefore the peak resistive force imparted into the structure, may be difficult to predict, and higher than expected, despite the simplicity of the structure, model and analysis.

This observation within the results is similar to the concept presented schematically in Figures 2 and 3. The results in Figure 6 thus highlight the importance of considering the overall balance of damping added, even within realistic ranges of (overall) damping, and especially for cases of structures with augmented damping. Hence, it may be considered that these results justify the overall proof of concept analysis presented in this work.

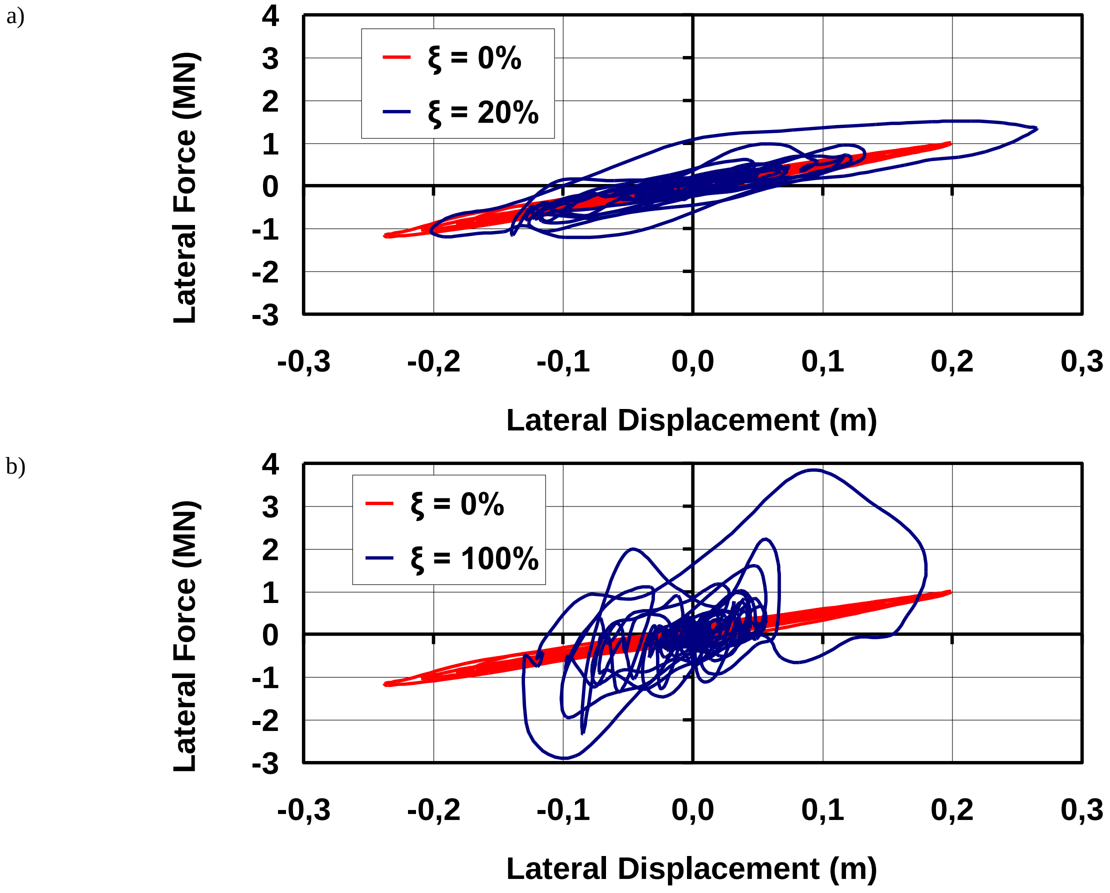

Figure 6: ***Lateral force versus displacement for a viscous brace structure with different effective damping and a column strength coefficient α of 1.0. The ground motion record used in these simulations was la02.***

Figure 7 presents the cumulative column displacement versus the column strength coefficient, α, for both the hysteretic brace and the viscous damper brace for a structure with a period of 4s. The column strength coefficient, α, is a factor α = [0, 1.0] that defines simulations with reduced column yield strength. Thus, α = 0.5 has 50% of the original yield strength, as defined in Section 3.2. The results in Figure 7 are a median result from the 10 ground motion records used. It is clearly evident in Figure 7 that the structure with the viscous damper brace has significantly lower cumulative displacement than the structure with the hysteretic damper brace. This result can be explained by the unique, initial concept presented in this paper, whereby axial column yielding reduces the velocity within the damper and acts as a stabilising mechanism to minimise the amount of column yielding.

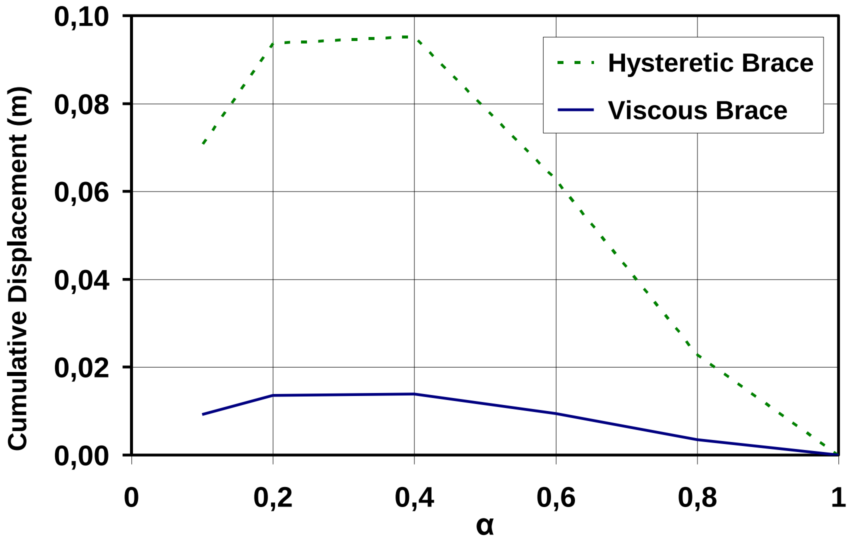

Figure 7: ***Median value of the column cumulative displacement versus the column strength coefficient α for a structure period T of 4s, a brace strength coefficient R of 3, an effective damping ξ of 35%, where the brace properties (α and R) are defined in Section 3.2.***

Figure 8 presents the same analysis as in Figure 7, but for a structure with a period of 2s, rather than ~4s. Again, there is a clear difference between the results for the hysteretic and damper braces, with the hysteretic brace resulting in significantly larger cumulative column displacement. Hence, the analysis and concept are robust across a range of periods.

It is also evident that as the column strength coefficient, α, is increased, the amount of cumulative displacement is initially increased. However, there is an overall trend towards a reduction as it approaches 1.0. This result is expected, as the lower column strength will naturally lead to an increase in yield displacement.

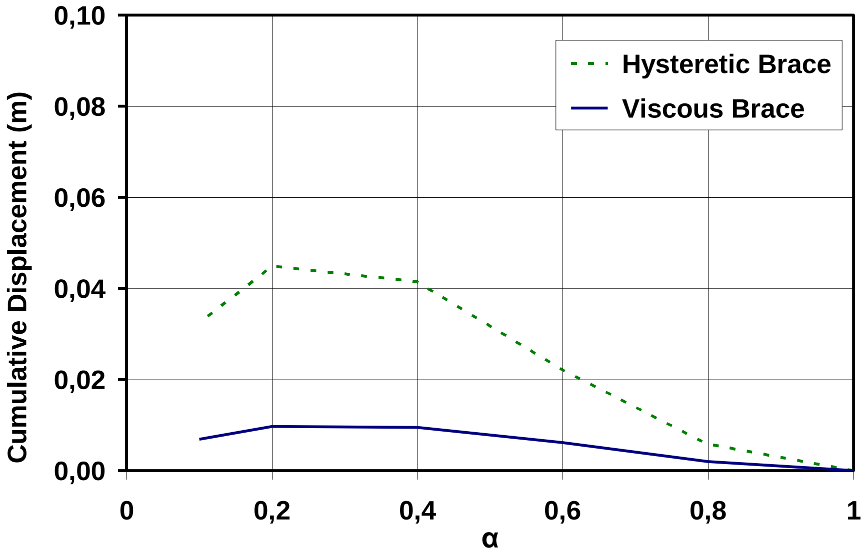

Figure 8: ***Median value of the column cumulative displacement versus the column strength coefficient α for a structure period T of 2s, a brace strength coefficient R of 3, an effective damping ξ of 35%.***

Figure 9 shows the same results as Figure 7 and 8, but for each individual record, thus showing the spread in results across ground motions. Interestingly, the order of the records, as labelled, are different for each device, showing how each device interacts in this simple analysis differently with the ground motion. Overall, the viscous brace (Figures 9b, d) has lower cumulative displacement across all records, as reflected for the median values of Figures 7-8. However, it should be noted that the spread across events is wider from maximum to minimum, for the viscous braced structures than for the hysteretic braced system.

The impact of brace ductility for the hysteretic brace (μ) was analysed in a sensitivity study across μ = 1-6. The cumulative displacement was then shown for ξ of 35% and a range of column strength factors, α = 0.2 – 1.0. The results in Figure 10 show a small linear trend over μ, with larger, expected column displacements as α is smaller. Overall, as brace design ductility (μ) rises cumulative displacement falls regardless of column strength.

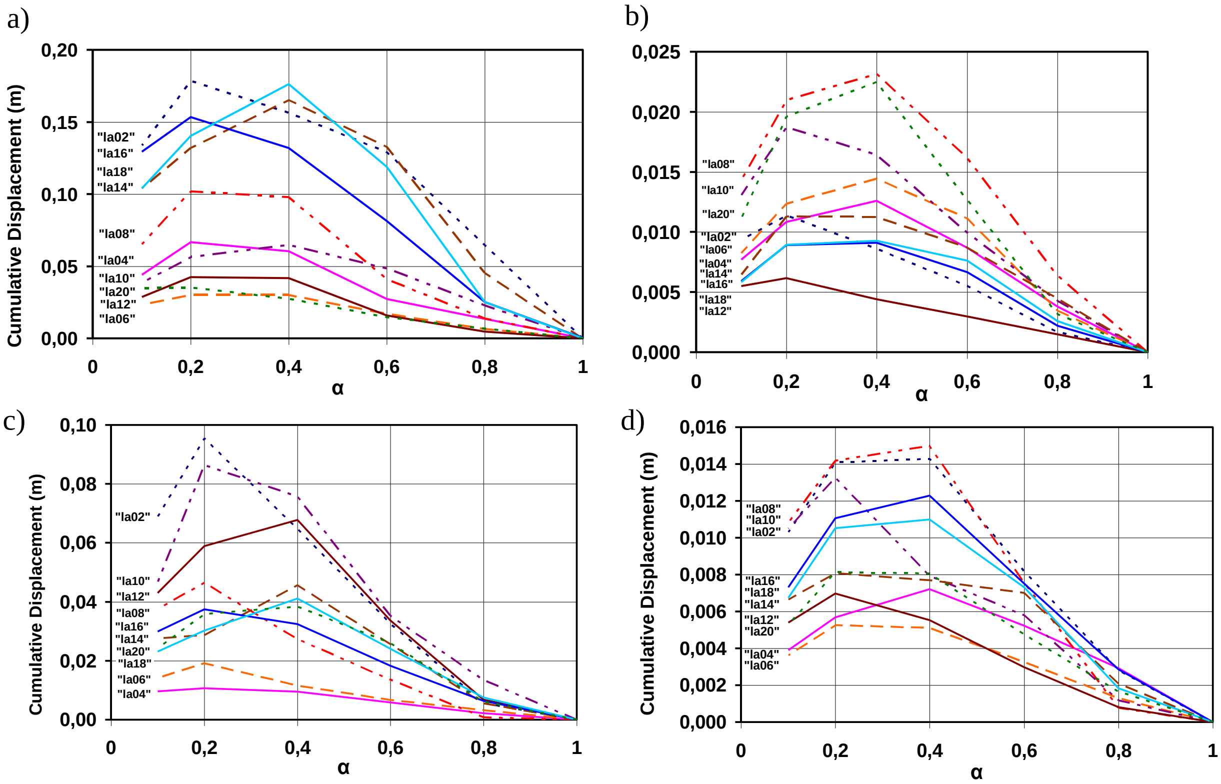

Figure 9: ***Column cumulative displacement versus the column strength coefficient α. a) hysteretic brace; b) viscous brace with a period T of 4s, a hysteretic brace strength coefficient μ of 3, an effective damping ξ of 35%. c) hysteretic brace; d) viscous brace, both with a period T of 2s, a hysteretic brace strength coefficient μ of 3, an effective damping ξ of 35%. All records are run with the earthquakes in Table 1.***

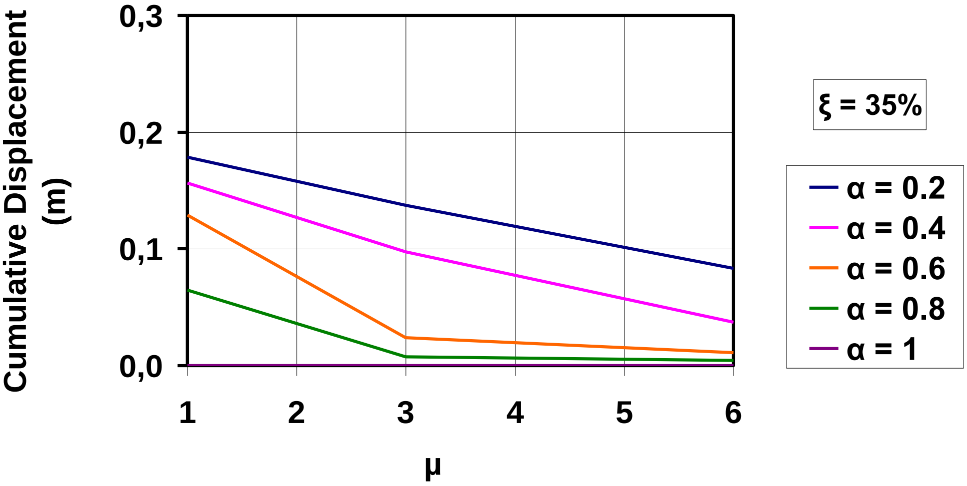

Figure 10: Column cumulative displacement with respect to brace ductility (μ) and column strength (α).

One potential limitation of this study is the range of damping ratios used (ξ), where 35% was the typical value chosen for analysis. This value is much larger than an un-augmented structure. However, it was chosen to represent a typically achievable value for a structure augmented with additional damping devices of any type (e.g. hysteretic, viscous, etc). Note that a sensitivity analysis, shown partly in Figure 6, shows no unexpected trends with this value. Thus, the choice of this value to demonstrate this principle, which was the main goal of this research, is robust to this value in reasonably achievable ranges.

Overall, the analytical investigation has confirmed the initial hypothesis that the use of viscous damping and the possible violation of capacity design methods have the potential to provide a self-stabilising system, where the onset of axial column displacement can reduce damping forces and prevent further yielding of the column. These results are consistent across linear viscous, bilinear yielding and hysteretic braces, as well as a range of periods and column strengths. Hence, the results and overall concept presented are robust to a range of types or methods of augmented damping.

In practice, the inclusion of axial column yielding may not be a desirable trait, and may be an aspect that provides a barrier to the consideration and uptake of such an approach in design. Particularly, when considering more advanced, next generation augmented damping systems or devices. In particular, it may be much more desirable to include a sacrificial steel fuse connection at the end of the damper-brace in series with the damper. This steel fuse element could be sized to prevent yielding of the column under large drifts and act as a genuine fuse element, rather than as a primary form of energy dissipation for response reduction, such as that typically done with so-called ‘yielding steel fuse bars’ (Bradley *et al,* 2008, Rodgers *et al,* 2008). Hence, there are alternatives and solutions whereby, in practice and pragmatically, dissipation can be separated from those structural elements responsible for load bearing and restoring forces without compromising the overall structural concept.

5.0 CONCLUSIONS

This research presented a novel and perhaps provocative concept of how structures with viscous bracing may benefit from violation of traditional capacity design techniques. The onset of axial column yielding can lead to lateral frame deflection resulting in no extension of a diagonal brace element. Therefore, a viscous damper placed within this diagonal will experience zero velocity, eliminating damping forces and potentially eliminating column yielding, in a manner that may lead to self-protecting behaviour, although at a loss of the expected dissipation. This concept is introduced within this paper and initial simulations indicate from cumulative inelastic column displacement that the penalty for violating capacity design requirements of a viscous system is much less than for a traditional hysteretic, yielding braced system. However, further studies, particularly experimental, are required to accurately illustrate and define this behaviour and thus provide more robust design recommendations for viscous and other augmented damping systems.

6.0 REFERENCES:

Bradley, B. A., Dhakal, R. P., Mander, J. B., Li, L. (2008). "Experimental multi-level seismic performance assessment of 3D RC frame designed for damage avoidance." *Earthquake Engineering & Structural Dynamics* **37**(1): 1-20. Doi: 10.1002/eqe.741

Rodgers, G. W., Solberg, K. M., Chase, J. G., Mander, J. B., Bradley, B. A., Dhakal, R. P., Li, L.. (2008). "Performance of a damage-protected beam–column subassembly utilizing external HF2V energy dissipation devices." *Earthquake Engineering & Structural Dynamics* **37**(13): 1549-1564 Doi: 10.1002/eqe.830

Somerville, P., Smith, N., Punyamurthula, S., and Sun, J. (1997). "Development of Ground Motion Time Histories For Phase II Of The FEMA/SAC Steel Project, SAC Background Document Report SAC/BD-97/04."