Inclusion of a Sacrificial Fuse to Limit Peak Base-Shear Forces During Extreme Seismic Events in Structures with Viscous Damping

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SUMMARY:

Viscous damping can be used to limit structural response due to seismic excitation. However, if large response velocities occur during an extreme seismic event such as a Maximum Considered Event (MCE), then significant damping forces can be created due to the damper velocity dependence. These damping forces are important as they must be resisted by the foundation. Therefore, methods to predict and limit peak damping forces are important. To avoid the possibility of large foundation demands a yielding fuse can be used in series with the viscous damper. The use of the sacrificial fuse allows the incorporation of a large capacity viscous damper which can dissipate large amounts of energy during lower-level seismic events without inducing unacceptably high foundation demands during the larger seismic event.

This paper shows the results of a spectral analysis on a single storey frame fitted with a brace, and with a viscous damper and a yielding fuse in series. Reduction factors are calculated for the base shear and displacement. It is shown that a reduced yield force has a small impact on the displacement response, but can significantly reduce the peak base-shear during extreme seismic events. By introducing the damper fuse with a yield force of 25% of the median base-shear force of the uncontrolled structure, 95th percentile displacement reduction factors increase from 0.85 to 0.96 (smaller displacement reductions) but 95th percentile base-shear reduction factors decrease from 2.0 to 1.4, which is a significant reduction in peak foundation demand. This analysis clearly outlines the design tradeoffs and considerations for realistic structural design scenarios using added viscous damping.

Keywords: Viscous damping, base-shear forces, foundation demands, structural energy dissipation

1. INTRODUCTION

Earthquakes cause significant structural damage, especially in the structural connections. It can be difficult to repair even if the weaknesses of the structure are known and intended by design. Recently, significant research has been undertaken to develop new energy dissipation technologies, which have made progress in reducing the overall seismic response of structures. Viscous dampers have been an important consideration for providing this response reduction (Pekcan et al, 1999).

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 columns remain elastic during an earthquake response cycle, and that any inelastic response will be concentrated in the formation of plastic hinge zones in the beams. In the case of structures with diagonal braces, with either supplemental viscous or hysteretic dampers, the damping forces impose an additional axial load in the columns that must be considered in design. If the additional axial loads in the columns due to the supplemental damping forces is neglected, axial column yielding may result. To avoid this situation, a yielding fuse is added to the brace, to limit the damping forces imparted into the columns and ultimately, the foundation. This design approach ensures yielding is limited to the brace despite larger total base shear forces.

The brace itself will likely have a linear force-displacement response, or if it includes some form of yielding steel, a bilinear response. Figure 1 presents the response of a brace with a viscous damper, assuming a sinusoidal displacement input. If the brace and frame are well matched, then the peak force in the overall combined response will be roughly equal to that of the structure itself, as seen in Figure 1. However, sometimes systems with large amounts of damping may be required to limit vibrations due to small earthquakes and the overall displacements of big earthquakes. In this case, there may be significant increases in total forces, as seen in Figure 2. If a yielding fuse is introduced on the brace then the peak force is lower than in Figure 2, as seen in Figure 3. Specifically, the inclusion of the yielding fuse in series with the damper allows the use of a viscous damper without the risk of introducing severe peak load to the foundation from the combined system.

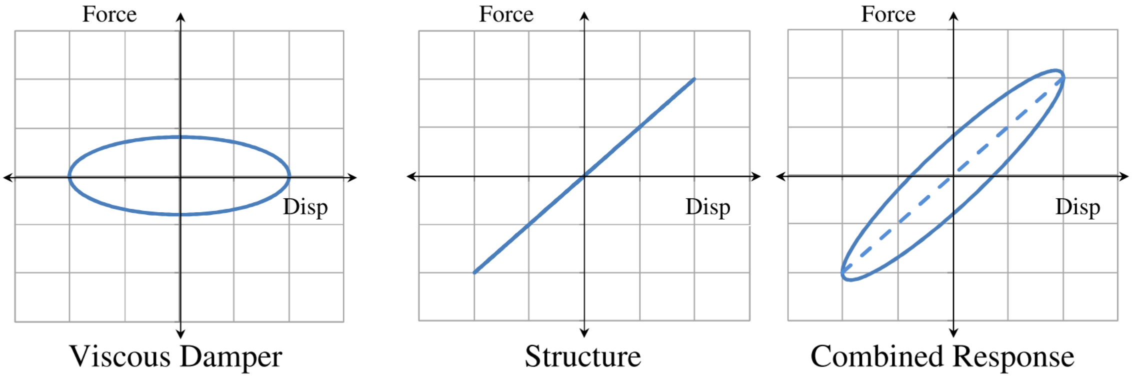

Figure 1. Schematic diagram of brace displacement response with well-matched damper and frame.

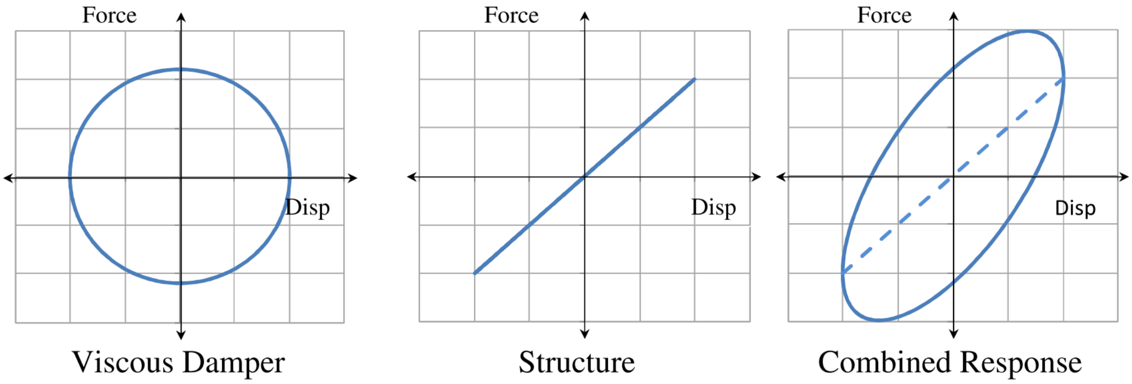

Figure 2. Schematic diagram of brace displacement response with poorly-matched damper and frame system, or a system that was subject to much larger velocities than expected.

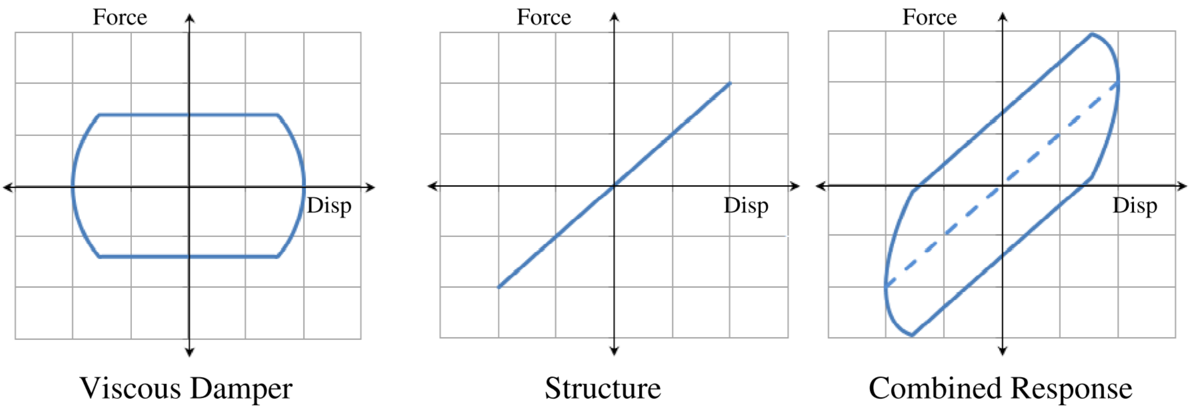

Figure 3. Schematic diagram of brace displacement response with a yielding fuse.

This research investigates the effect of the sizing of this fuse and its yield force on the spectral response of a structure. The specific aim of the research is to investigate the effect of a sacrificial fuse to limit damping forces so that a large damper can be used allowing large amounts of energy to be absorbed at even small response cycles, without overloading the structure on larger response cycles with higher velocities. The results will thus delineate this range of design tradeoffs.

2. METHOD

2.1. Models

The reference model is a linear fixed base system. An equivalent representation, in Figure 4, is a mass, spring, damper system. The spring and the damper describe the stiffness and the damping of the structure. For this study, the damping ratio value is $\xi = 5\%$.

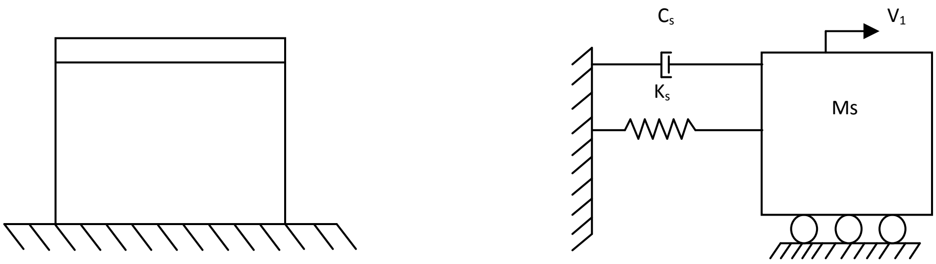

Figure 4. schematic diagram of the linear model.

To limit seismic response, a brace with a viscous damper is connected to the structure by a yielding fuse. Figure 5 shows this system and equivalent representation. The mass m_D is used to add a degree of freedom between the viscous damper and the yielding fuse, and is chosen as 0.001kg. The fuse has an initial linear stiffness, $k_D = 10k_s$, and a given yield force F_y. It should be noted that the two systems in Figure 5 are not identically equal, and that the linear model is a simplified version of the diagonal brace for simplicity of modelling.

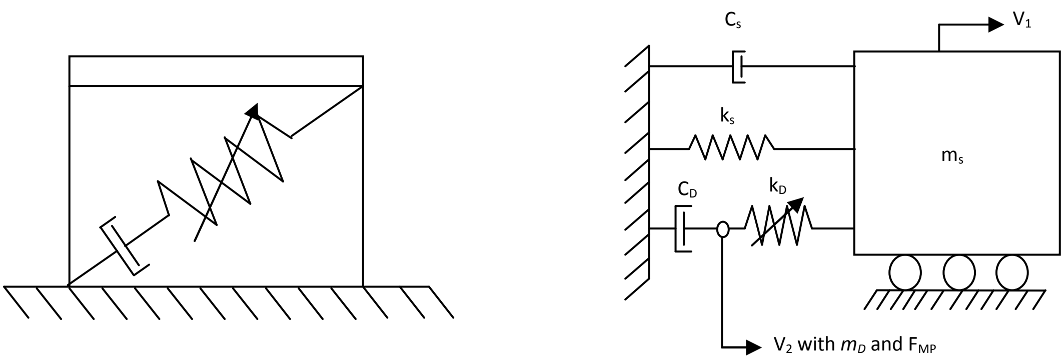

Figure 5. Schematic diagram of the structure with the truss.

A Menegotto-Pinto model (Menegotto and Pinto, 1973) is used for the nonlinear yielding fuse. It defines the force of the non-linear fuse:

$$F_{MP} = \frac{k_D(z - z_{reset}) + F_{reset}}{\left(1 + \left|\frac{k_D(z - z_{reset}) + F_{reset}}{F_y sign(z)}\right|^{\beta}\right)^{1/\beta}} \tag{2.1}$$

Where F_y is the yield force, k_D the initial stiffness, Z_{reset} and F_{reset} are the displacement and the force at the last reset point, where the structure changed direction, and $z = V_1 - V_2$ as defined in Figure 5.

The equations of motion for the system in Figure 5 are defined:

$$\begin{aligned} m_s\ddot{V}_1 + c_s\dot{V}_1 + k_sV_1 &= -m_s\ddot{x}_g - F_{MP} \\ m_D\ddot{V}_2 &= -c_D\dot{V}_2 + F_{MP} \end{aligned} \tag{2.2}$$

Where $\ddot{x}_g$ is the ground motion acceleration and Equation (2.2) can be written in matrix form:

$$\begin{bmatrix} m_s & 0 \\ 0 & m_D \end{bmatrix}\begin{Bmatrix} \ddot{V}_1 \\ \ddot{V}_2 \end{Bmatrix} + \begin{bmatrix} c_s & 0 \\ 0 & c_D \end{bmatrix}\begin{Bmatrix} \dot{V}_1 \\ \dot{V}_2 \end{Bmatrix} + \begin{bmatrix} k_s & 0 \\ 0 & 0 \end{bmatrix}\begin{Bmatrix} V_1 \\ V_2 \end{Bmatrix} = \begin{Bmatrix} -m_s\ddot{x}_g - F_{MP} \\ F_{MP} \end{Bmatrix} \tag{2.3}$$

To calculate the motion of the structure for a given ground motion and calculate the forces, the Newmark-Beta method is used.

2.2. Applied Loading

The research utilizes three earthquake suites from the SAC project, with 10 different time histories and two orthogonal directions for each history (Sommerville et al, 1997). The three suites represent ground motions having probabilities of exceedance of 50% in 50 years, 10% in 50 years, and 2% in 50 years in the Los Angeles region, and are referred to as the low, medium and high suites, respectively. Response statistics can be generated from the results of each probabilistically scaled suite. This research uses only the design level medium suite.

2.3. Spectral Analyses

To analyse these structures, spectral response plots were generated for the structural displacement and the total base shear, for structural periods from 0.1-5.0s in increments of 0.1s. The total base shear is defined as the sum of the structural force and the resisting forces from the truss, where the structural force is the base shear for the linear structure of Figure 4. The structural force is an indication of the required column strength, and the base shear is an indication of the required foundation strength.

The response and force reductions achieved by the addition of the truss are represented by reduction factors, normalized to the linear case results for each ground motion. These reduction factors enable easy comparison of the effect of structural changes, as well as for the stiffness and yield force of the yielding fuse. They are calculated at each period for each earthquake for displacement and base shear.

Results are presented for the median, 5th and 95th percentile reduction factors at each structural period. The time step used for the analysis is 0.001s for period, T, lower than 0.6s, and 0.01s for all other periods, based on a convergence analysis. The structural mass is constant and equal to 1000kg and the period is varied by changing column stiffness. For the linear case, C_s is calculated to provide 5% internal structural damping. For the supplemental damping system, three cases are considered with additional damping of 30 and 60% of critical added, such that $C_d = 6{*}C_s$ or $12{*}C_s$ respectively. These values cover a broad range of damping to examine the impact on response.

2.4. Analyses and Comparisons

The statistical values used to indicate the change in response reductions factors are the median, 5th and the 95th percentile results for displacement and base shear reduction factors. The results are given for different values of the yielding force in the fuse. Specifically:

- F_y = 0 to prove that the model used is valid. It thus yields immediately and no force is transmitted to the damper. Results should give reduction factors at 1.0 to match the linear case and validate the model.
- F_y = 25%, 50%, 75% and 100% of the median base shear from the linear model results at each period. These cases represented a reasonable design range. Results show the effect of F_y on performance.
- $F_y = \infty$, the limit case, equivalent to simply adding a linear viscous damper without limiting its forces or input.

3. RESULTS

3.1. Displacement Reduction Factors

Figure 6 shows the effect of F_y on displacement response with 30% added damping. It shows that there is no significant difference between the plots, so the value of F_y in this range has little impact on the displacement achieved for these ground motions. Median and 95th percentile results vary between 50-60% (of linear case) and 60-80% respectively.

When F_y decreases the reduction factors tend towards 1.0, especially for higher periods. Hence, they approach the linear case results, ie: as F_y decreases the results move towards the same values of reduction factors when F_y = 0. In this case, the lower yield force in the sacrificial fuse limits the energy dissipation in the damper. Hence, the displacement reductions are smaller (higher reduction factor). Outside of this effect, there is little charge in the spectra on the 5th-95th percentile range across the suite.

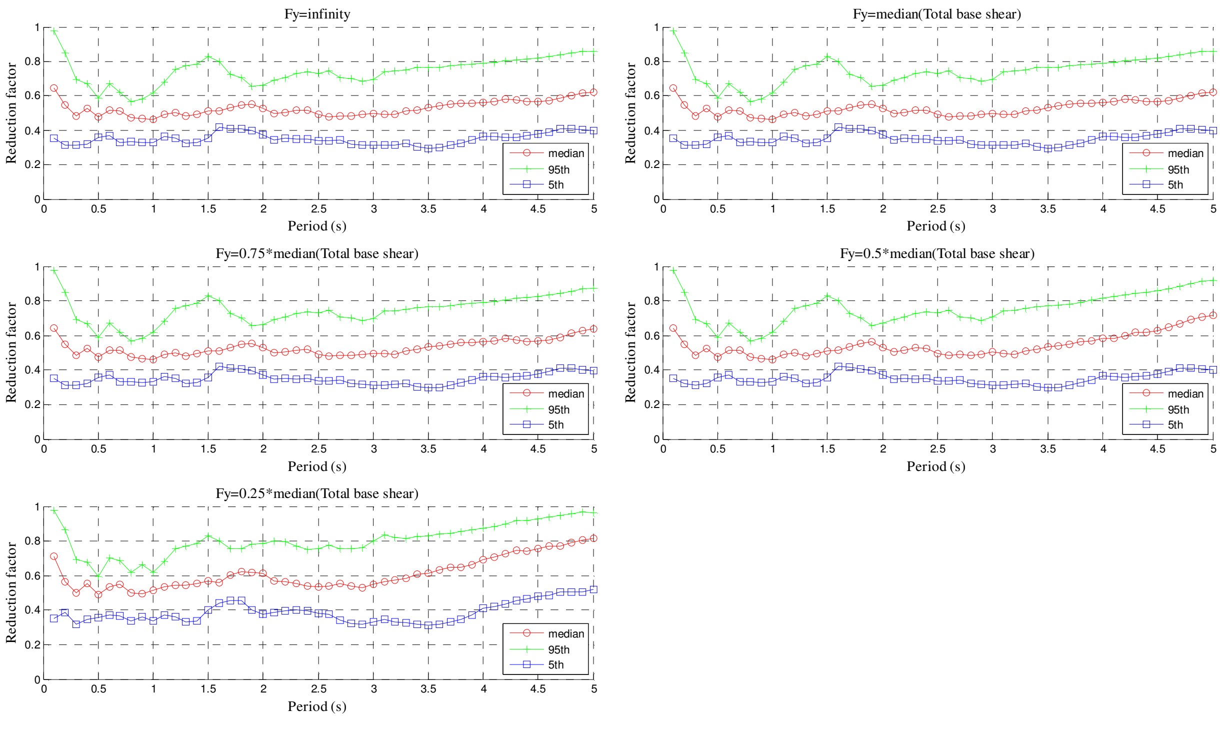

Figure 6. Reduction factors for displacement for different values of F_y for $F_y = \infty$, and F_y = 25%, 50%, 75% and 100% of the median base shear force for the linear model case. ξ_s = 5%, ξ_d = 30%.

Figure 7 presents the same results as Figure 6, but with ξ_d increased to 60% of critical. This analysis provides an indication of the importance of the fuse in structures with more added damping. It is evident that the displacement reduction factors do increase towards 1.0 (smaller reductions) with lower fuse yield strength, as the maximum damper contribution is reduced by the lower yield force. At long periods the median reduction factors increase from 0.5 to 0.85 as the fuse yield force reduces from 1000 times the median base-shear (linear spring case) to 25% of the median base-shear of the uncontrolled structure. The spread of the results remains similar, showing that the 5^{th} and 95^{th} percentile results increase also.

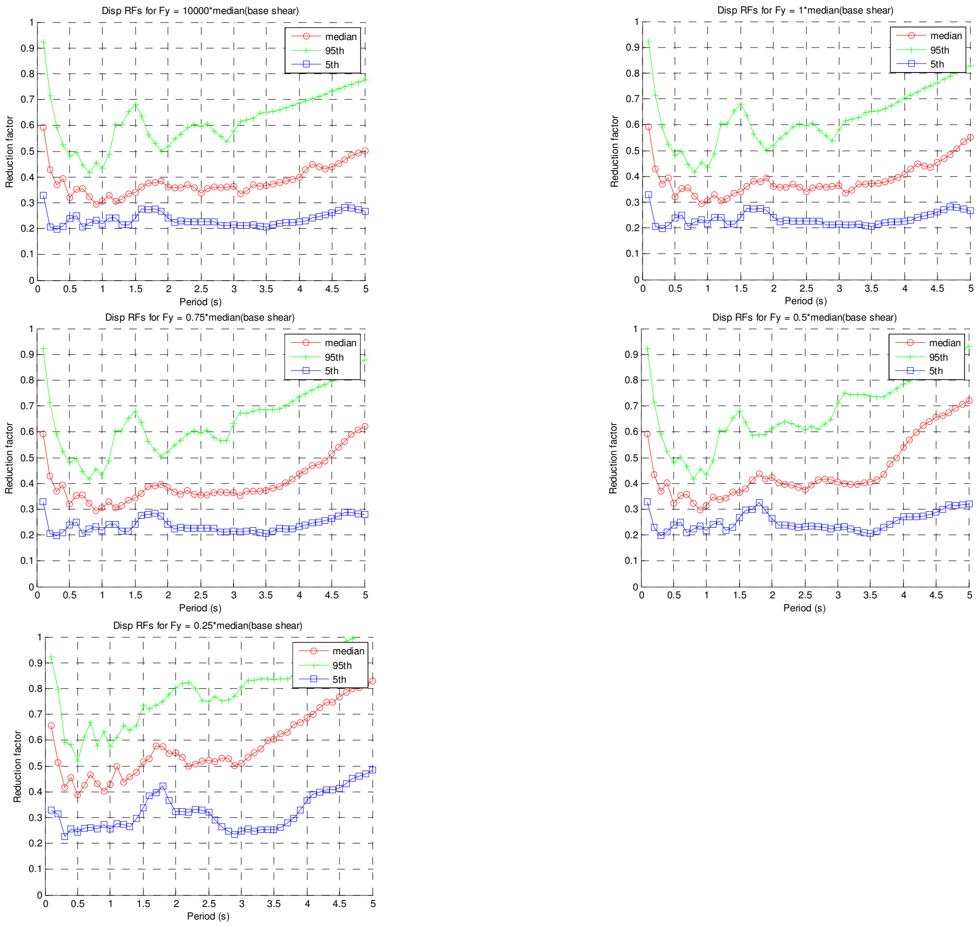

Figure 7. Reduction factors for displacement for different values of F_y for $F_y = \infty$, and $F_y = 25\%$, 50%, 75% and 100% of the median base shear force for the linear model case. $\xi_s = 5\%$, $\xi_d = 60\%$.

3.2. Base-Shear Reduction Factors

Figure 8 shows the base shear reduction factors for the different values of F_y with $\xi_d = 30\%$. Unlike the displacement reduction for the same level of added damping in Figure 6, the yield force has a significant effect on the base shear, especially at low periods. Median values vary between 50-120% over all periods showing the trade-off between reduced displacement and increased base shear. The 95^{th} percentile results show similar trends and define the reasonable upper limit on foundation demand.

Figure 8 also shows that the reduction factors decrease when F_y decreases, (towards a limit of 1.0 when $F_y = 0$). This trend can be seen more clearly at higher periods. In particular, by reducing the fuse yield force to 25% of the median base-shear, the displacement reductions are smaller as seen by higher reduction factors, closer to 1.0 in Figure 6. Concomitantly, the base shear reduction factors decrease in Figure 8. However, by comparing the results for $F_y = \infty$ to $F_y = 0.25$*median(base-shear) it can be seen that while the 95th percentile displacement reduction factor at long periods (T = 5.0s) increases from 0.85 to 0.96 in Figure 6, the 95th percentile base-shear reduction factor drops only from 2.0 to 1.4. Therefore, in extreme events with larger expected velocity inputs, the sacrificial fuse meets the goal of limiting the peak foundation demand, an important response consideration. Equally, the displacement reductions can be interpreted as being relatively small (<1%) in this example, for relatively large (40%) increases in base shear.

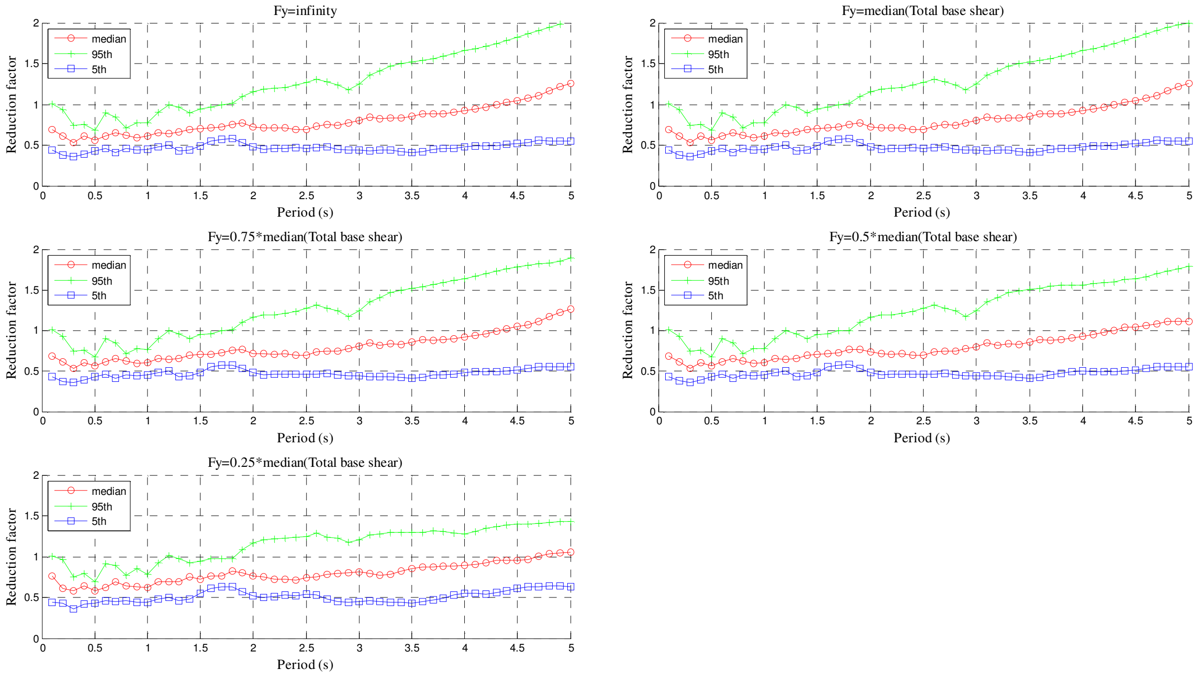

Figure 8. Reduction factors for base shear for different values of $F_y = \infty$, and F_y = 25%, 50%, 75% and 100% of median base shear. C_s = 5%, C_d = 30%.

Figure 9 presents the base-shear reduction factors, the same as in Figure 8, but with ξ_d = 60%. It is evident in Figure 9 that the larger damper leads to substantially increased base-shear (RF >> 1.0) for the extreme events corresponding to the 95th percentile. With a linear elastic fuse (F_y = 1000*median base-shear), the peak base-shear at long periods for the 95th percentile event is up to 3 times that of the structure without added damping. As the fuse yield force is reduced, the median base-shear is reduced, particularly at long periods. Of particular note is the large reduction in the peak base-shear for the extreme event (95th percentile) from 3.0 down to 1.45 for the 5.0 second period.

The overall result of these two figures shows that fuses can have significant impact on displacement and base shear in highly (viscous) damped structures. However, this effect is primarily seen in longer period structures (T > 2.5 seconds). For shorter period structures there is notable change in the 95th percentile response levels, but median levels, typically used in design codes and analyses, are only little affected, as seen in Figures 8-9.

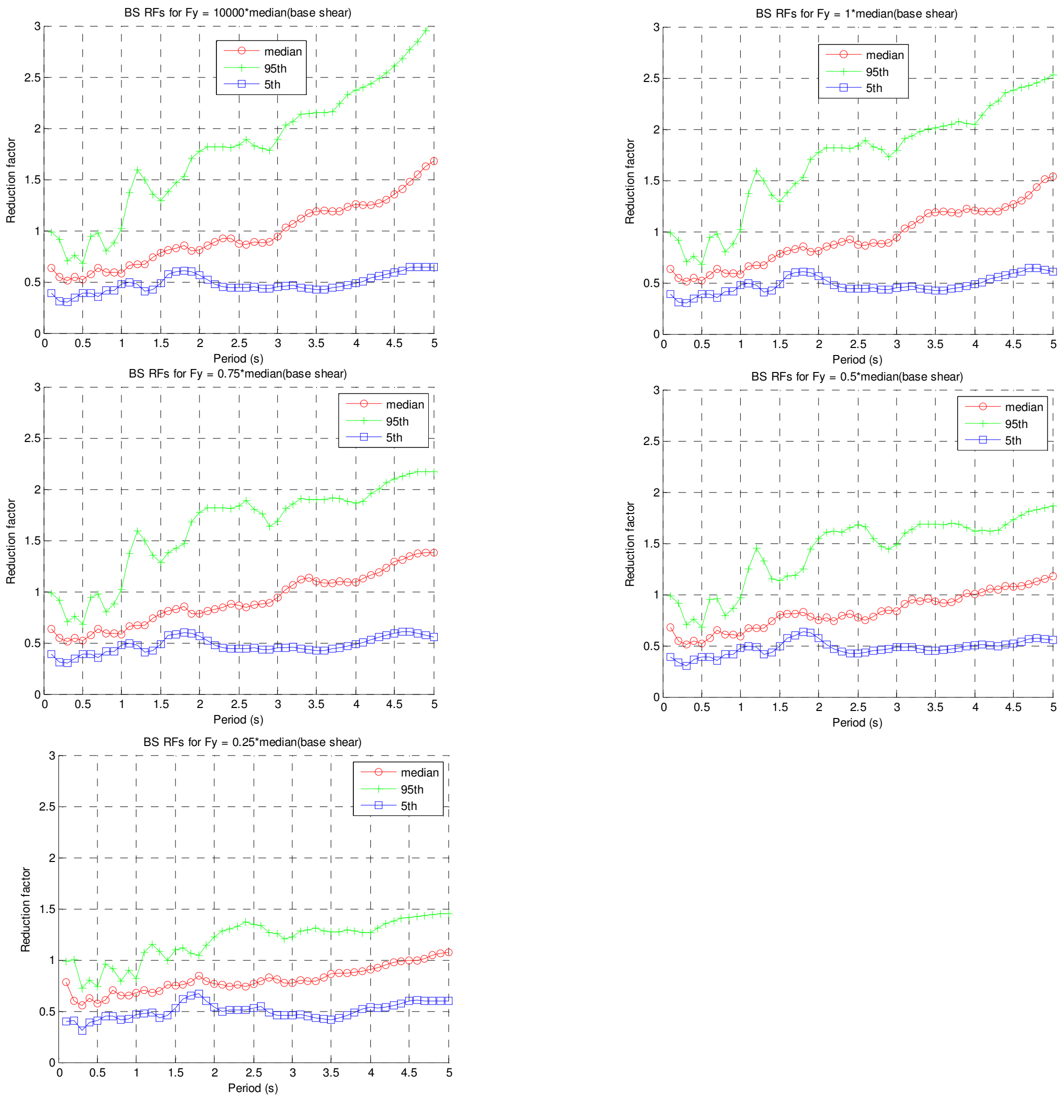

Figure 9. Reduction factors for displacement for different values of F_y for $F_y = \infty$, and $F_y = 25\%$, 50%, 75% and 100% of the median base shear force for the linear model case. $\xi_s = 5\%$, $\xi_d = 60\%$.

3.3. Hysteresis Loops

Figure 10 presents the structural response for one earthquake with $\xi_d = 30\%$, that corresponds to the 95th percentile results and structural period $T = 5.0$s. It shows the force versus displacement hysteresis loop for the total base shear and the column displacement for the extreme values of $F_y = 25\%$ of median base shear and $F_y = \infty$. The peak damping force is smaller with $F_y = 0.25$*median (base shear), and consequently the supplemental damping system absorbs less energy. Therefore, the peak base shear force is noticeably less. However, the structural displacement is slightly increased as a result.

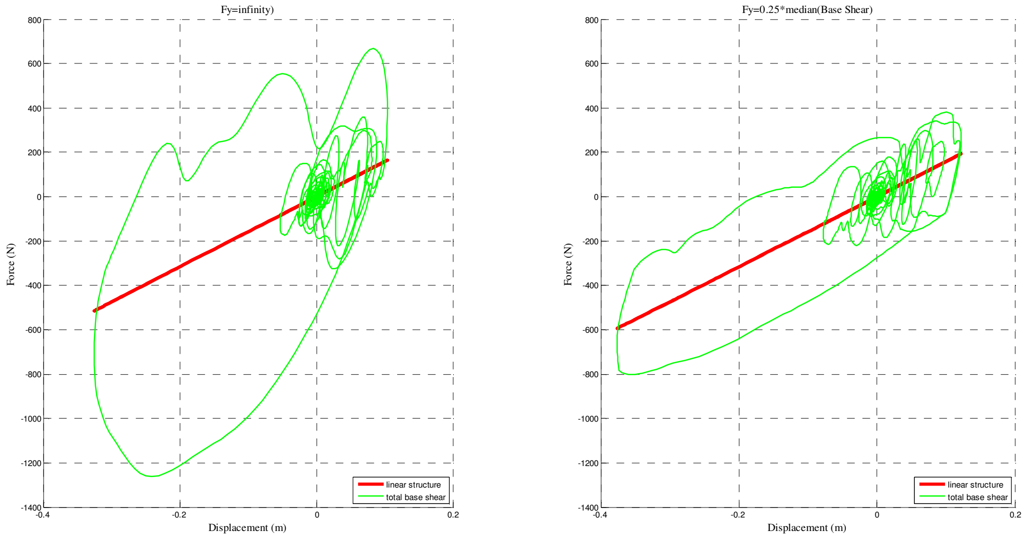

Figure 10. Lateral force versus displacement for the extreme value of F_y. For $T = 5.0$s and the earthquake corresponding to the 95th percentile results. $C_s = 5\%$, $C_d = 30\%$.

3.4. Fuse Displacement

Figure 11 presents the fuse displacement for ξ_d = 30%, expressed as a percentage of the structural spectral displacement. It gives an idea of the size of the sacrificial fuse that should be use in these structures. The value of the percentage is higher when the yielding force is smaller. However, it is always much smaller than 1.0, so the fuse doesn't need to be large. As expected, the lower yield forces lead to much larger displacements within the fuse. The $F_y = \infty$ case has non-zero displacements as, while there is no yielding, there is still elastic displacement within the fuse. The fuse displacement is, as expected, larger for the ξ_d = 60% case (not shown here), which would require a larger fuse.

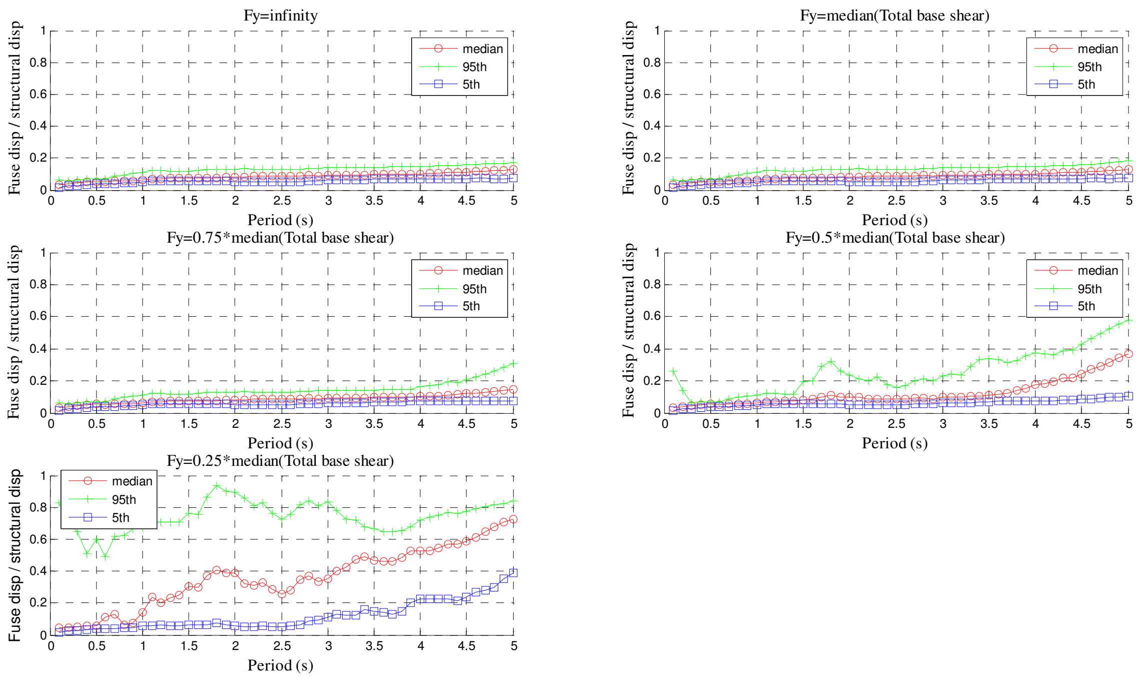

Figure 11. Percentage of displacement of the fuse compared to the displacement of the mass

3.5. Limitations

The model used for this study is chosen to represent a range of possible specific design structures. However, it is modelled by only a mass and two parameters C_S and k_S. Hence, the results don't show the effect of multiple nodes or hinges in the beam. The model has to be more realistic to better evaluate the motion of a specific structure. However, the results do capture the broad design trends and fundamental tradeoffs, and is thus useful to assess potential improvements and risk in design. In addition, the spectral analysis, while not specific, does present these design tradeoffs in a manner that matches current design procedures. Finally, the use of median and 95th percentile responses show the results in a way that might best match probabilistic or risk-based design approaches. Hence, while the analysis is limited in specificity, it presents results that may be more broadly used to guide design in current design frameworks

A Menegotto-Pinto model was used for the nonlinear yielding fuse. However, several possible other models could have been used to model the nonlinearity of the fuse. In this case, the simplicity and relevance of the Menegotto-Pinto model represented an acceptable choice. The analysis approach is readily generalizable to other non linear models depending on the specific application or case.

4. CONCLUSIONS

This research presents an analysis of the tradeoffs in design of braced frames fitted with supplemental viscous dampers. The addition of yielding fuses within the brace ensures peak foundation demands are limited, controlling this variable. It also allows the use of larger viscous dampers as a result, presenting new design opportunities, particularly for longer period structures. The results show that reducing the fuse yield force limits the damping force and consequently leads to smaller displacement response reductions, as expected. However, the real strength of this approach is the ability to limit the peak base-shear, and, in particular, the 95th percentile base-shear, and the median base shear used in design analyses when considering longer period structures.

The importance and need to reduce and account for the peak foundation demand for extreme events has been shown in the recent Christchurch earthquakes, a strong case-study for this research. The model and approach developed in this study is readily generalised, and could be used for further research to show the effect of other parameters or other supplemental systems. Overall, the results presented provide an overall set of design tradeoffs and guidelines suitable for use in performance based design of structures using supplemental damping.

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