5. Conclusions

5.1 Summary

The following were the primary objectives of this study:

- Determine if a certain damper type (nonlinear $\alpha<1$, linear, or nonlinear $\alpha>1$) is best suited for use in a structure subjected to a certain ground motion (near-field or far-field)
- Determine if viscous dampers, more specifically a certain type of viscous damper, can decrease residual deformations
- Determine if viscous dampers, more specifically a certain type of viscous damper, can reduce the dispersion in the IDA curves
- Relate residual displacements to dispersion in the IDA curves
- Compare response of a damper for a coefficient calculated at 1 and 5% story drifts
- Compare the results of the IDA method for the different damage indices
- Provide an assessment of the use of IDA as a seismic behavior evaluation tool

To achieve these objectives, the study used an approach called Incremental Dynamic Analysis (IDA) to assess the performance of steel moment-resisting frames with different types of fluid viscous dampers when subjected to earthquake ground motions. The dampers tested had α values of 0.5, 1.0, and 1.5. The damping coefficients when linear dampers were used, α=1.0, were calculated for a structure with a 5%, 10%, 15%, and 20% critical damping ratio. Nonlinear damping coefficients were calculated when α=0.5 and 1.5 to provide a 10% and 20% critical damping ratio and the nonlinear dampers were calibrated for 1% and 5% drift.

The structure with each type of damping was subjected to nonlinear inelastic time history analysis for 12 different ground motions, six near-field and six far-field. Each ground motion was scaled to intensities that range from $S_a(T_1,10\%)$=0.1 to 2.0 g by 0.1 g increments. Originally it was assumed that the chevron damper braces would not be allowed to yield, but this assumption was reconsidered and some additional analyses were done with yielding braces. The structure including yielding braces with α=0.5 at 1% drift, α=1.0, and α=1.5 at 1% drift was subjected to five of the ground motions at intensities that ranged from 0.1-0.5g by 0.1 g increments and 0.5-1.9 by 0.2 g increments. Peak base shear, peak interstory drift ratio (IDR), damage index, and residual displacement were the response measures recorded for each nonlinear time history. IDA curves were created to summarize and compare the results of the structure with different damping types subjected to the different ground motions.

5.2 Conclusions

5.2.1 Damper Type

The type of damper used in a steel moment-resisting frame affects structural behavior when subjected to earthquakes as follows:

- In a system where braces remain elastic increased critical damping ratio of linear fluid viscous dampers improves the response of the structure with respect to peak IDR and damage. At the same time the trends in the response of peak base shear with increased damping ratio vary. Before yield, the peak base shear is decreased with increased damping ratio, and after yield the peak base shear increases.
- Linear fluid viscous dampers reduced drifts and damage for the structure subjected to both LA and NF ground motions, while producing comparable base shears for the two types of ground motions. This is contrary to a conclusion made by other researchers who claim that linear damping is not effective in improving structural response when subjected to near-field earthquakes.
- When dampers are used in a structure where the damper braces are not allowed to yield, dampers with α=1.5 are best suited to decrease drifts and damage. However, at the same time these dampers produce substantially large base shear demands that may present design problems. In the structures where braces do not yield, dampers with α=0.5 produce the least amount of drift and damage reduction. In some instances, the drift response for dampers with α=0.5 is worse than the response with just linear viscous damping at 5% critically damped.

However, the dampers with α=0.5 are the most effective at limiting the amount of base shear produced when dampers are used.

- When the dampers are used in a structure where the damper braces are allowed to yield, dampers with α=1.5 become less effective in reducing drift. The response of the system with yielding braces and α=1.5 is similar to the response of the system without yielding braces up to the intensity that causes the yielding. After this point the dampers become ineffective and the response of the structure worsens. The yielding braces have a similar effect on the systems that use the linear damper, except the intensity at which the dampers become ineffective is higher than for α=1.5. Finally, the yielding braces do not have much effect on the systems that use dampers with α=0.5. These behavior trends for the different dampers with the yielding braces were expected. The reason that the dampers with α=1.5 are most affected is because they produce the highest damper force at a given earthquake intensity and therefore cause their braces to yield first. When using dampers in a structure, the braces need to be designed to remain elastic in the range of intensities where the dampers are expected to be effective.
- The results of the study do not lead to any significant conclusions about which damper type is best suited for steel moment-resisting frames subjected to an earthquake type near-field or far-field. The trends in behavior for the structures with a certain damper type were consistent for both the near-field and far-field ground motions.

5.2.2 Residual Displacements

The results of this investigation lead to the following conclusions regarding damper type and residual displacements:

- When used in combination with braces that are not allowed to yield, dampers with α=1.5 are best suited to improve the response of structures that are subjected to ground motions that produce large residual displacements.
- Allowing the damper braces in the structure to yield significantly decreases residual displacement reductions for intensities greater than the yield intensity.

Dampers with α=1.5 are affected the most by yielding braces, followed by linear dampers. The effect on dampers with α=0.5 is almost negligible. This is expected because dampers with α=1.5 produce increasingly high forces, while dampers with α=0.5 are force limiting.

- The shape of a residual displacement IDA curve for a certain damper type is very similar to the shape of that damper's force-velocity relationship.

5.2.3 Dispersion

This study, through the use of the standard deviation IDA curves, has shown the following:

- Structures that use dampers with α=1.5 experience the least amount of dispersion between the drift responses for the different ground motions.
- The most amount of dispersion in the drift response for the different ground motions is displayed when dampers with α=0.5 are used.
- As with the residual displacement IDA curves, the shape of a drift standard deviation IDA curve for a certain damper type is very similar to the shape of that damper's force-velocity relationship.

5.2.4 Relating Residual Displacements and Dispersion

A comparison of the standard deviation of drift and the average of residual displacements for the structure subjected to the LA and NF ground motions was used to relate residual displacements and dispersion. This comparison clearly displayed a relationship between the two, which only strengthens the argument that residual displacement is a significant cause of dispersion between the IDA curves.

5.2.5 Calibration Parameter

The nonlinear dampers were calibrated according to Section 3.2.5.2 to achieve a basis for comparison. Maximum damper displacement is one of the calibration parameters and was varied to investigate its effect on structural behavior. The results of the experiments show that the shape of the drift, residual displacement, and standard deviation IDA curves very closely matches the shape of the tested damper's force-velocity relationship, which is also a function of the displacement parameter.

When IDA curves of two systems with different damper types are compared with each other, one system may be more favorable for a lower range of earthquake intensities, while the other becomes more effective at higher intensities. The intensity where the transition takes place in the comparison of the two different systems corresponds to the intersection point of the two dampers' force-velocity curves. When the dampers were calibrated for 1% drift, the transition point in the comparison between α=1.5 and 0.5, or α=1.5 or 1.0, or α=1.0 and 0.5 occurred at an intensity in the elastic range of structural response. In the elastic range the differences in behavior of the structure with different damping types are small compared to the differences at higher intensities. Therefore, the dampers with α=1.5 at 1% drift seem to be the best suited to reduce IDR, residual displacement, and dispersion for a large range of intensities. When the dampers were calibrated for 5% drift, the transition point in the comparison between α=1.5 and 0.5, or α=1.5 or 1.0, or α=1.0 and 0.5 occurred at an intensity in the inelastic range of structural response. At these intensities the differences in behavior of the structure with different damping types are large with respect to the differences at lower intensities. Therefore, at intensities before the transition point, the dampers with α=0.5 are best suited to reduce drifts, residual displacements, and dispersion, but after this point α=1.5 becomes more effective in reducing these responses. This leads to the conclusion that comparisons between different types of damping require an understanding of the damper behavior in the situation in which it is used. To accomplish this, the following should be done:

- Determine whether or not the structure that is incorporating the dampers will remain elastic or will undergo yielding.
- Understand how the damper behavior will change if the structure yields.
- Determine an appropriate range of intensities where the dampers are expected to be effective.
- Determine the effect that the parameter used to calibrate the dampers for comparison has on the comparison in the range of intensities for which the dampers are expected to perform.

- If a certain damper type has a favorable behavior, select the calibration parameter so that the behavior remains favorable in the expected range of intensities.

5.2.6 Comparison of Damage Indices

The study selected two different damage indices, the Park and Ang Damage Index (DI) and peak interstory drift (IDR), to characterize structural damage caused by the different earthquakes. A comparison of the two different damage indices has led to the following conclusions:

- Both DI and IDR can be used to show that damage is decreased with increased damping ratio
- Both DI and IDR can be used to show that dampers with α=1.5 are the best suited to reduce damage when the damper braces are not allowed to yield
- DI can provide the damage done to a member, a story, or the entire structure, while IDR can only give the damage for a certain story
- IDR is easier to calculate

5.3 Limitations of Study

The limitations of the study conducted include:

- Structure was modeled in 2-D, ignoring any 3-D behavior such as torsion
- The 9-story steel moment-resisting frame was the only structural model used
- Only nonlinear dampers with α=0.5 and 1.5 were tested
- The force-velocity relationship of the nonlinear damper element in *Perform* was approximate
- Yielding damper braces were only modeled in the 20% critically damped structure with linear dampers and nonlinear dampers calibrated for 1% drift subjected to only five different ground motions

5.4 Recommendations for Further Research

One suggestion for future research on fluid viscous dampers used in steel moment-resisting frames is the optimization of damper placement when the response is inelastic; *research has been done for elastic response,* such as Takewaki and Uetani (1999).

Throughout this study the damper's placement was fixed, but there may have been a different configuration that would make the dampers more effective. A further study could also expand investigation of dampers by including different sizes of structures. The structural behavior in this study was only for a 9-story structure and it would be interesting to see how this behavior changed when the dampers were used in shorter or taller buildings.

The research has shown that the gains in reduction of drift, residual displacement, and dispersion made by using dampers with α=1.5 comes at the cost of high base shear forces. Therefore, further research should focus on developing passive hybrid devices that combine the behavior of the dampers with α=1.5 and 0.5. An ideal hybrid device would perform with a hardening force-velocity relationship for lower velocities and a softening relationship at higher velocities. This type of damper would be beneficial because it could significantly reduce response, as observed with α=1.5 devices, while being force limited like the dampers with α=0.5. Certain semi-active devices may have the ability to do this by changing the shape of the piston orifices.

Incremental dynamic analysis has proven to be a useful tool for providing understanding of structural behavior for a large range of circumstances. The use of the IDA approach in this study has produced insight into the effect of fluid viscous dampers for a wide range of structural behavior. Past research on this topic generally only tested the dampers with a few earthquakes all scaled to some design intensity. This has led to several conclusions about the effect of dampers on structural response, such as peak base shear, that are not correct for all the possible scenarios. Therefore, any future research involving structures subjected to dynamic forces should consider IDA as the most appropriate approach available.

Further research involving IDA should focus on making it more effective and efficient. There is a lot of useful information is produced with IDA, and it would be beneficial to have computer software that does the following:

- Scales the ground motions so that they could easily be used in the program that processes the data.
- Post-processes any data output by the processor in order to obtain the response measures that are of interest, such as drift, base shear, brace forces, residual displacement index, or damage index.
- Graphically displays the IDA curves with options to store and retrieve multiple curves that could be displayed on a single plot.
- Have the ability to adjusts the axes of the IDA plot in order to zoom in at certain intensities
- Possesses options to graphically display information for each point that makes up an IDA curve. Useful information may include: acceleration, velocity, and displacement time history for ground motions at the intensity of the response, response spectrum curve for ground motions at the intensity of the response, time history of the response measured, the location in the structure where the peak response occurs, and a snap-shot time history plot that illustrates the sequence of yielding in the structure.