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Diaphragm Design Considerations for Buildings Utilizing Viscous Dampers

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ABSTRACT

In the quest to improve building resilience and reduce structural damage during earthquakes, viscous dampers have proven to be highly effective. These devices reduce vibration amplitude and mitigate dynamic load impacts on structures. A key benefit is that they are velocity-based, with velocity and displacement out of phase, improving structural performance without altering stiffness.

However, this out-of-phase characteristic can lead to design challenges. Engineers may not properly design the diaphragm and frame to account for forces exerted by the dampers. It is common to design diaphragms for inertia acceleration without considering the need to transfer these loads to the dampers for effective damping. If not properly designed, load transfer can be compromised, making the dampers ineffective.

This paper explains how to design diaphragms and frames in buildings with viscous dampers, emphasizing the interaction between them. Traditional approaches often focus solely on diaphragm acceleration, neglecting damper forces, leading to suboptimal performance and reduced seismic resilience

This limitation is crucial, especially when retrofitting buildings with diaphragms that cannot effectively transfer loads. Engineers must ensure damper configuration does not increase axial load on beams or account for it in their design. Without considering these points, dampers may not perform as expected, and building performance could deteriorate. This study demonstrates how to design diaphragms and frames for viscous dampers to ensure their benefits are fully realized.

1 INTRODUCTION

Viscous dampers have been used to control structural vibrations for decades, starting in aerospace and expanding to civil engineering in the 1990s (Christopoulos and Filiatrault, 2006). A viscous damper typically consists of a steel cylinder filled with a viscous fluid (e.g. silicone oil). A viscous damper generates a resisting force that is dependent on velocity. As illustrated in Figure 1, the velocity dependent viscous damping force varies according to Eq. (1):

$$F = Cv^{\alpha}.sign(v) \quad (1)$$

where F represents the damping force, v denotes the velocity, C_{VD} is a constant expressed in units of force divided by velocity raised to the power of α, and α is a constant that determines the non-linearity of the damping force. In a linear viscous damper, α equals 1, which signifies a direct correlation between force and velocity, as shown in Figure 1.

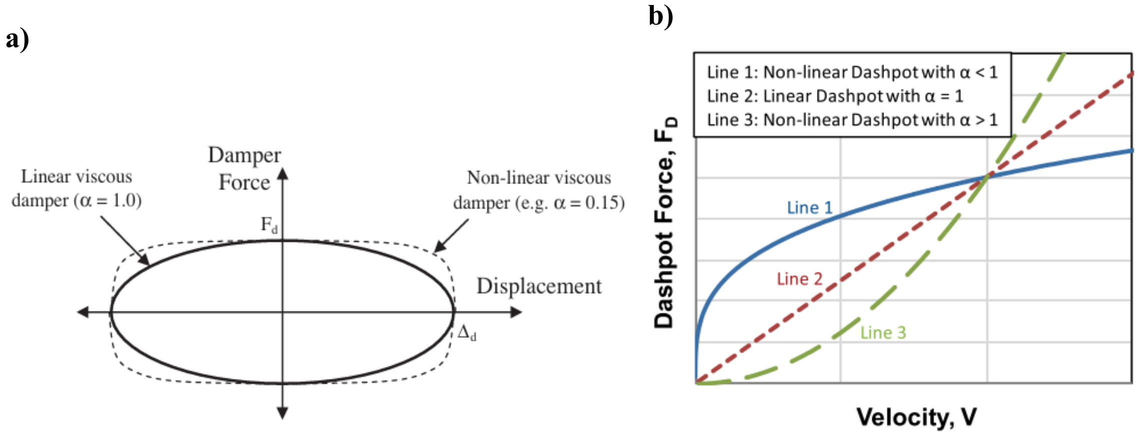


Figure 1: a) force displacement, b) force-velocity of linear and nonlinear viscous damper.

One of the main advantages of viscous dampers is that they operate based on velocity, with velocity and displacement being out of phase, which enhances structural performance without altering stiffness. Nonetheless, this out-of-phase characteristic can present design challenges. The maximum base shear when installing the viscous damper is not the same as with a displacement device like a Buckling Restrained Brace (BRB), which happens at maximum displacement. As shown in Figure 2, the maximum base shear occurs between maximum and zero displacement.

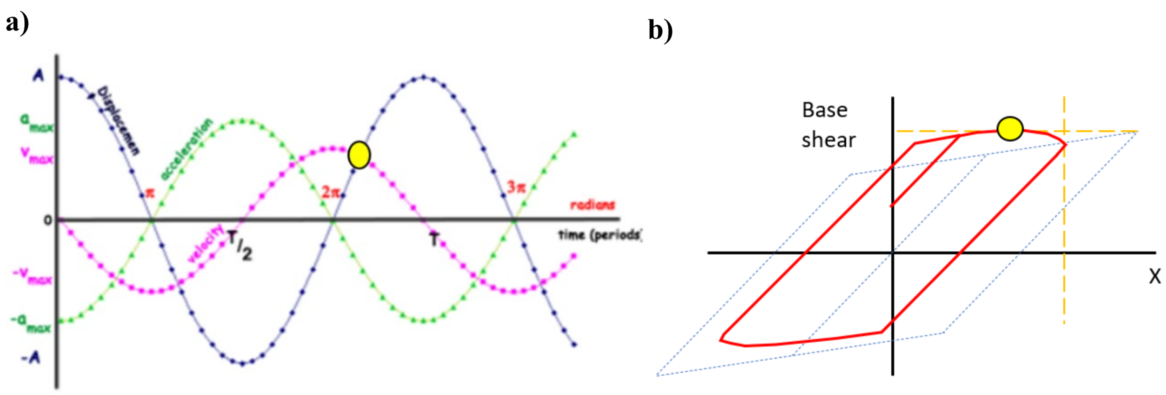


Figure 2: Displacement, velocity and acceleration relation in different time step, b) base shear-displacement of the structure with a viscous damper

Thus, time history analysis helps to understand the maximum acceleration of diaphragm and base shear of the building. However, it is important to note that this process requires considering absolute acceleration rather than relative acceleration.

Eq. 2 outlines the motion of a system equipped with a viscous damper. Here, $\ddot{x}_g$ denotes ground acceleration, x represents relative displacement, and $\dot{x}$ signifies relative velocity. The variables m, k, C, and C_{VD} correspond to mass, stiffness, damping coefficient, and viscous damper coefficient, respectively.

$$m\ddot{x} + kx + C\dot{x} + C_{VD}\dot{x} = -m\ddot{x}_g \tag{2}$$

$$kx + C\dot{x} + C_{VD}\dot{x} = -m(\ddot{x}_g + \ddot{x})$$

The demand on the diaphragm must account for absolute acceleration, which is essential to address the total inertial effects acting upon it. This includes both the structural and ground motion components, represented as $(\ddot{x}_g + \ddot{x})$.

In addition, after determining the demand on the diaphragm, the next step involves assigning the demand and reaction to capture the performance of the diaphragm and beams. The strut and tie method are utilized to evaluate the performance of the diaphragm and beams (NZS 1170.5) There are two approaches to consider for distributing the reaction demand on the resisting system in the strut and tie method:

1. Assigning springs based on the stiffness of the resisting system.

2. Assigning reaction demand based on a 3D model analysis.

However, if the first method is used, the stiffness of the viscous damper needs to be considered. Although the viscous damper does not increase the building's stiffness, one of its benefits poses a challenge in how it should be accounted for. This paper also compares two methods of analysing diaphragms and beams to evaluate which one better captures the effect of the viscous damper.

Therefore, in designing the structure with viscous dampers, several key factors must be carefully considered to ensure the appropriate benefits are captured. This paper outlines the parameters that need to be considered in the design of the diaphragm and frame with viscous dampers.

2 CASE STUDY

2.1 Building performance

To understand the effect of the viscous damper, the nonlinear time history analysis of two-story building with nonlinear viscous damper (α=0.5) under El Centro 1940 earthquake are evaluate, using ETABS (Figure 3).

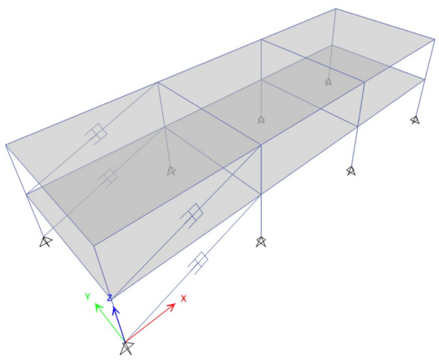


Figure 3: two-story linear frame with nonlinear viscous damper (α=0.5)

The building performance are evaluated on the two critical time steps:

1. Time step maximum base shear occur.
2. Time step that the maximum viscous damper occurs

Then it shows how to capture the diaphragm demand on these times.

The Figure 4 shows the base shear and viscous damper force under an earthquake. It shows that the maximum base shear happened at T=16.46S and it is 9304kN and maximum viscous damper force happened at 6.92S with FVD= 3244kN.

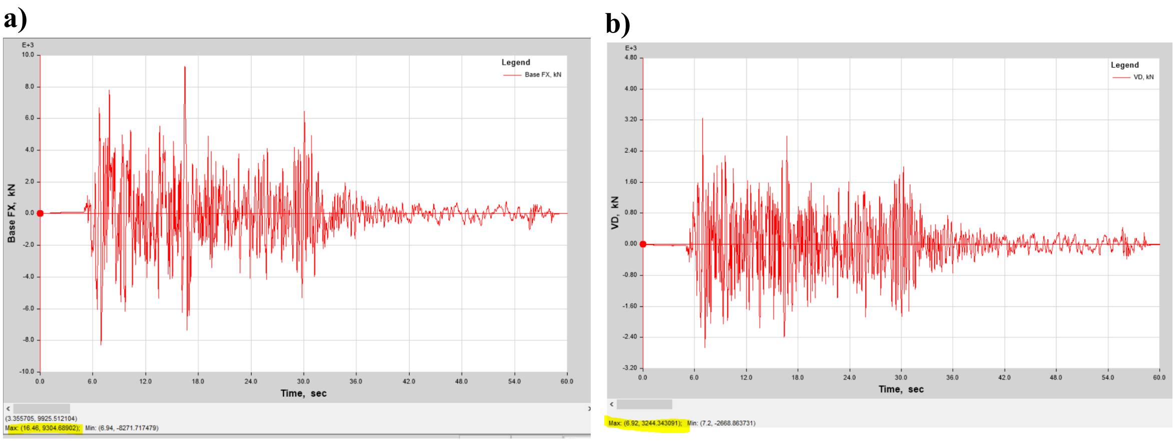


Figure 4: a) Base shear, b) Viscous damper force under El Centro earthquake.

Figure 5 shows the shear force, viscous damper force, applied and resultant force at level one under earthquake at T=6.92s. At this time step the inertial demand on diaphragm is 3915kN (mass * absolute acceleration of floor).

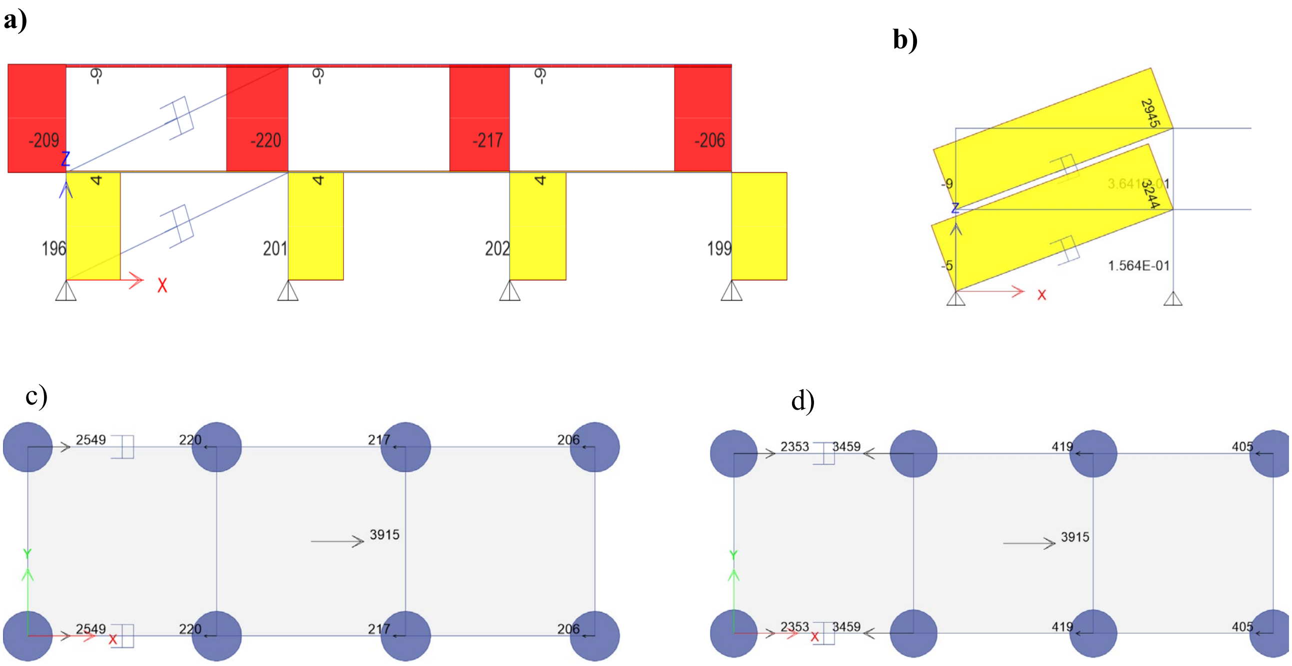
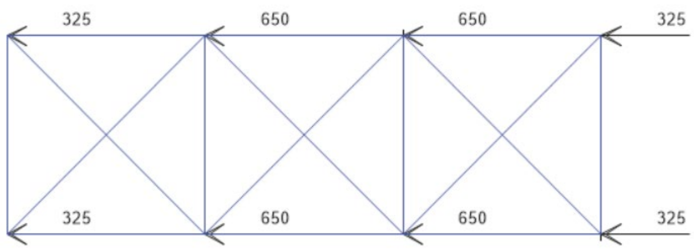


Figure 5: a) shear force, b) viscous damper force, c) applied force at level 1, d) resultant force at level one under Earthquake at T=6.92s that

2.2 Diaphragm demand

For designing and assessing the diaphragm, two methos that explained in the introduction are evaluated and compared. In the first method, the diaphragm demand is distributed on each node based on area. The diaphragm load is 3900kN that means 325kN to corner node and 650kN to middle one, as shown in the Figure 6a. As all column has same stiffness, same spring value could assign on that. The result shows that the maximum axial load on the member is and 162kN. However, as it shows in the Figure 5c,d in the location the viscous damper connection the demand and resultant force are different from other nodes that is ignored in this method. That means, if the diaphragm evaluated based on this method the results does not show effect of the viscous damper, Figure 6b.

a) Applied load



b) Axial demand on memeber

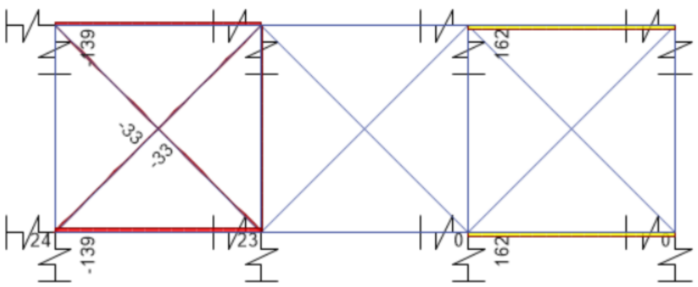


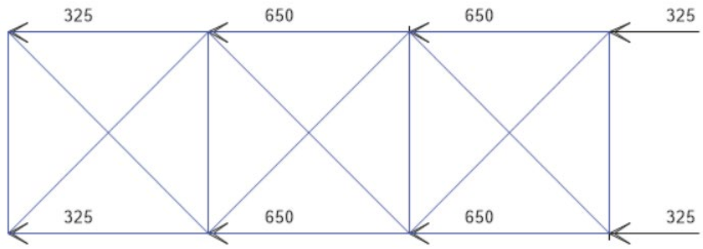
Figure 6: strut and tie method a) demand on each node b) axil load

To capture the effect of viscous damper and design the diaphragm of the structure with viscous damper, it needs to applied reaction load of the viscous damper and frame based on the time history analysis to capture the accurate diaphragm and beam force.

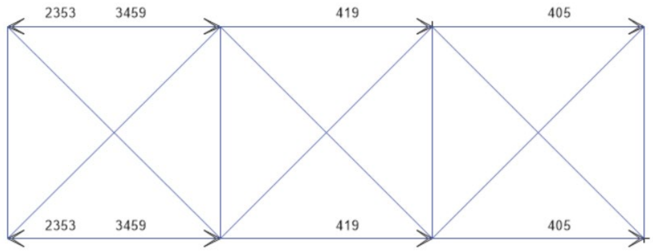
Figure 7a shows the reaction force applied to each node based on the nonlinear time history analysis, that is the second method. The results show that with this method the axial load and demand on diaphragm could be captured. The axial load on the beam is 2676kN that was not captured it in the previous analysis method as it does not consider the effect of viscous damper. axial load on beam need to consider and play an important rule for moment frame as the tension demand on the beam reduce dramatically the moment capacity of the beam and failure mechanism could be changed.

Ignoring this demand can lead to catastrophic outcomes. Hence, not only does the addition of a viscous damper fail to improve the building's performance, but it could also exacerbate the situation if these factors are overlooked. Evaluating the diaphragm and beam are more critical for retrofitting the building with cold mesh as the cold mesh could not distribute the load.

a) Applied force



b) Reaction of resisting system



c) Axial deamnd on member

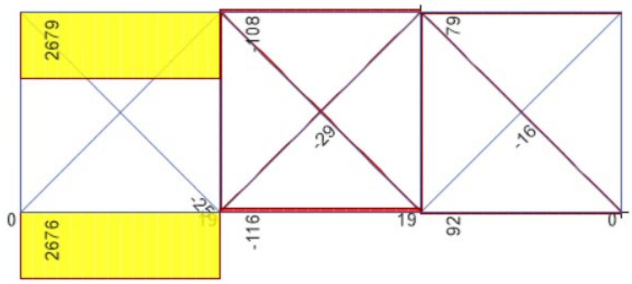


Figure 7: strut and tie, a) demand on each node b) reaction load b) axial load

3 CONCLUSION

The analysis and design of structures incorporating viscous dampers several critical considerations for ensuring structural integrity and safety. Key factors include:

1. Demand on Diaphragm: The demand on the diaphragm is calculated by the product of the mass and the absolute acceleration.

2. Diaphragm Check Based on Viscous Damper and Frame Reaction: It is essential to evaluate the diaphragm's performance based on the reaction of both the viscous damper and the frame. Notably, their maximum reactions do not occur simultaneously.

3. For designing the diaphragm, it is crucial to consider the reaction force of the viscous damper to understand its effect thoroughly. This ensures that the load is not uniformly distributed on the diaphragm but is instead properly accounted for based on the dynamic interaction between the damper and the frame.

4. Axial Load Considerations: Evaluating axial loads on beams is essential, particularly for moment frames. The tension demand on the beam can significantly reduce its moment capacity, thus affecting the overall performance of the structure. Accurate assessment of these loads ensures the appropriate design and retrofitting measures are implemented.

By integrating these considerations into the design process, optimal performance and safety of the building structure can be ensured.

4 REFERENCES

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