Influence of Damper Sub-System Stiffness on the Structural Performance of a System Equipped with a Viscous Damper

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Abstract

Viscous fluid dampers are often incorporated into structures without much consideration for the inherent elastic flexibility of the damper sub-system and associated connections. However, this damper sub-system flexibility can alter the phasing of damper and structural forces and influence the overall structural response. This paper investigates how damper sub-system stiffness affects the overall displacement response and total system force of a structural system in a seismic event. The single-degree-of-freedom (SDOF) model consists of an elastic structural element, a viscous damper and an elastic spring that represents the damper sub-system flexibility. This model is subject to ground motion acceleration excitations. Results from ground motion simulations indicate that if a damper is designed assuming a rigid sub-system, the median peak displacement response can be up to 33% higher than expected, depending on the level of added supplemental damping, the damper sub-system stiffness, and the period of vibration of the structural system. For this reason, it is recommended that in order to limit the impact of phasing effects, designers should ensure that the damper sub-system stiffness is five to ten times the stiffness of the main lateral load resisting system.

Keywords: Supplemental damping; Damper connection flexibility; Viscous damping; Structural Dynamics; Damping reduction factors.

INTRODUCTION:

Traditional building design methods often rely on the yielding of key structural members through the development of plastic hinges in beam end zones to provide a method of dissipating seismic response energy. This approach to capacity design has been effective in preventing structural collapse and preventing the loss of life during moderate to severe earthquakes. However, in several recent major earthquakes it has been shown to induce damage that may be uneconomic to repair, leading to significant economic loss from both direct damage costs and the associated downtime [Elwood *et al.*, 2015].

Due to these issues with conventional sacrificial capacity design principles, the use of supplemental damping is seeing increased uptake, both in the retrofit of existing structures and in the design of new structures. Structures designed using so-called “low-damage design” principles, such as the use of rocking walls or frames, are particularly suitable candidates for the use of supplemental damping, due to their typically low inherent damping.

Viscous fluid dampers have seen increased usage in structural applications in recent decades [Christopoulos *et al.*, 2006]. These viscous dampers, which produce damping forces through the flow of a viscous internal fluid, have been applied to both buildings and bridges in seismically active regions. Viscous dampers are often considered a favourable choice to provide supplemental damping in structures located in seismic regions because they dissipate seismic structural response energy and can improve structural response, without introducing significant additional structural stiffness. The absence of added stiffness will generally mean that viscous dampers do not increase the demand on foundations. Additionally, the application of viscous dampers in new and existing structures can be cost effective [Pettinga *et al.*, 2013].

The velocity-dependence of the resistive forces produced within viscous fluid dampers requires modified design and analysis strategies. Many different methods can be found in the literature such as Gluck *et al*. [1996], Ramirez *et al*. [2000], Lin *et al*. [2003], Kim *et al*. [2003], Silverstri *et al*. [2010], Sullivan and Lago [2012], Lavan [2012], Lavan [2015], and Puthanpuravil *et al*. [2017].

Determining the optimal location, number, and size of added viscous fluid dampers to achieve a target value of overall system equivalent damping has been the focus of a lot of research in recent years. This process is further complicated when considering viscous fluid dampers with both linear and non-linear force-velocity response.

In most of these design methods to size the viscous dampers, the inherent elastic flexibility of the damper sub-system and associated connections is not considered. Therefore, these methods do not account for the influence that the elastic deformation of the damper sub-system has on the overall structural performance.

One of the few studies to explicitly consider the damper sub-system flexibility was Dong *et al*. [2016]. This damper sub-system flexibility consideration was part of a large-scale experimental test of a multi-story steel frame building fitted with nonlinear viscous fluid dampers. The results from this study provided the interesting observation that the deformations of structural components and connections adjacent to the dampers caused the local deformations of viscous fluid dampers to be different to the inter-story displacement between the connection points.

This phenomenon was referred to as the "brace flexibility" effect by the authors and caused the damper responses to be partially out-of-phase with the structural responses. As a consequence of the brace flexibility effect, the damper sub-system provided an added stiffness to the steel frame. The term "brace" here indicates the damper sub-system that provides connection between the damper and the main structure. Furthermore, Dong [2016] used an equivalent linear elastic-viscous model to simulate a damper-sub-system component in order to further investigate the effect of sub-system stiffness on the response of a frame structure. This study stated that a more flexible sub-system stiffens a structure and the sub-system stiffness also affects the effective damping of the structure.

Current seismic design procedures available for structures equipped with viscous dampers are mainly intended to identify the amount of damping required to limit the structural displacements to a desired amount, and this can result in a set of damper coefficients over the height of the structure. Although some of these procedures do highlight the need for the designer to account for the flexibility of the sub-system, there is an absence of guidance on how to explicitly include such effects in design.

Furthermore, the definition of what constitutes a rigid connection is unclear, and based on the literature described above, a flexible sub-system would lead to a different response than expected. For this reason, this paper reports on a study by Xie et al. (2019) to investigate how the damper sub-system stiffness changes the response of a structure, and to what extent the sub-system stiffness can affect the equivalent damping provided to the system. The results of the study will be used to provide a practical indication of how stiff a sub-system needs to be to enable it to be effectively considered as rigid during design.

DAMPER AND STRUCTURAL MODELLING:

The damping force induced by the flow of a damping fluid within a viscous damper can be defined using Equation (1) below.

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

Where F is the damping force, v is the velocity between the damper shaft and the surrounding cylinder, C is the damping constant (dependent upon physical design parameters), and α is the exponent constant that defines the linearity of a viscous damper. A linear viscous damper adopts an α value of 1.0, and if α is greater or less than 1.0 it makes the viscous damper nonlinear.

In practice, a nonlinear viscous damper typically possesses an α value between 0.1 – 0.3 [Sullivan and Lago, 2012]. Nonlinear viscous dampers with low values of α have the advantage that uncertainty in the expected "in-service" damper velocity, due to uncertainty in the ground motion and structural properties, leads to a much smaller uncertainty in the likely damper response force. The non-linear force-velocity profile and the "saturation" of force at larger velocities can allow designers to use a lower over-strength factor than they might otherwise require if using a damper with a linear force-velocity response.

Furthermore, if oscillated to the same level of displacement at the same frequency and peak force, a nonlinear viscous damper is able to dissipate more energy than a linear viscous damper, due to the more rectangular and less elliptical hysteresis loop it possesses, as shown in Figure 1.

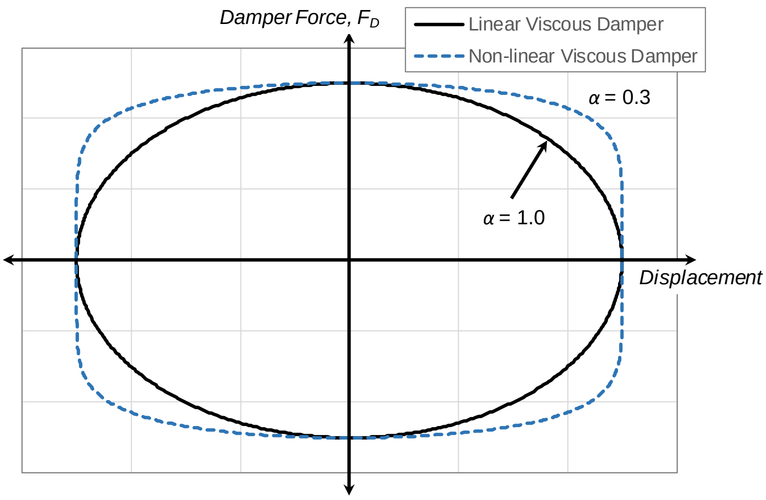


Figure 1. Comparison of linear and non-linear viscous fluid damper response when subjected to the same displacement amplitude and peak force. The non-linear damper encloses a larger area and dissipates more energy.

Figure 2 presents an equivalent elastic single degree-of-freedom (SDOF) structural model that has been developed as part of this study (Xie et al. 2019). The model consists of a linear elastic spring in parallel with a viscous dashpot that represents inherent structural damping of 5% of critical. In parallel to this simple structural model, supplemental damping is modelled as viscous damper element in series with an elastic spring, otherwise known as the Maxwell model. The viscous dashpot is defined by a damping coefficient C_d and velocity exponent constant α_d.

The linear elastic spring in series with the supplemental damper represents the sub-system stiffness, and it is defined by a value of K_d. The structural component of the SDOF model is defined by an elastic material which is connected in parallel with the Maxwell component, which represents the structural lateral resisting system stiffness and has a stiffness of K_s. A viscous dashpot, representing the inherent damping of the system, is connected in parallel with both the structural and Maxwell components.

For this study, the inherent damping is modelled as linear elastic damping ($\alpha_I = 1$) using a damping constant representing 5% of critical damping. This 5% of critical value is kept constant for all analyses. The level of damping provided by the supplemental damping is increased and is modelled as a linear viscous damper within this study.

The SDOF model also consists of two nodes. Node 1 is fully fixed and node 2 is only allowed to displace laterally (aligned with the z co-ordinate shown in Figure 2). Despite the simplicity of the model, it represents a more direct relationship between the structural component, the viscous damper, and the sub-system, without the influence of other factors that would be present in a multi-degree of freedom system.

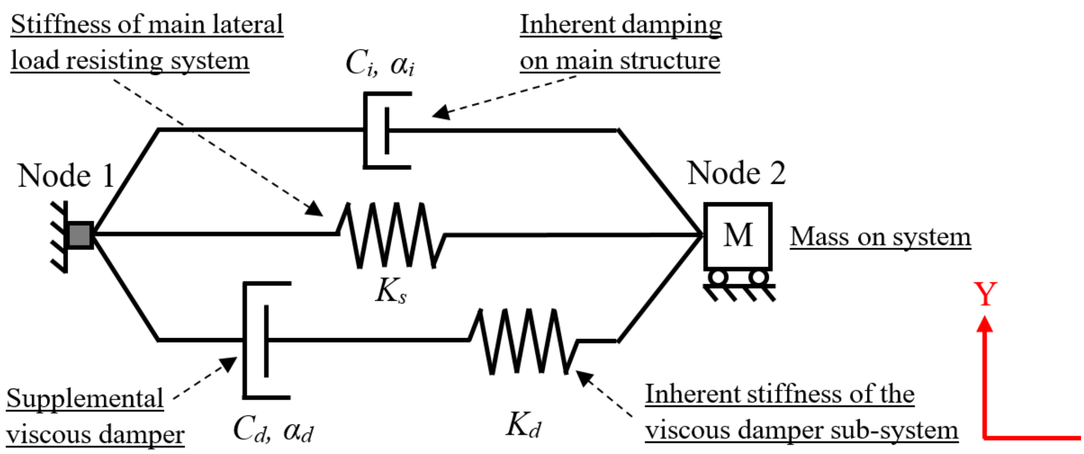


Figure 2. SDOF structural model developed in OpenSEES.

To conduct the numerical time-history analysis for this study, this SDOF model is implemented into OpenSEES [Mazzoni *et al*., 2006]. In OpenSEES, the Maxwell model is represented using the *ViscousDamper* material in the OpenSEES database. It is an uni-axial material that is coded and implemented by Akcelyan *et al*. [2018]. The *ViscousDamper* material models the viscous dashpot and the sub-system spring as a single material, which allows users to define C_d, α_d, and K_d. When using the new *ViscousDamper* material in this research, a maximum time step of 0.0002s is found to be adequate for earthquake excitations. Coarse time step values can be used in some situations, such as with longer periods, without inducing any numerical instability.

INFLEUNCE OF DAMPER SUB-SYSTEM FLEXIBILITY ON SYSTEM RESPONSE TO EARTHQUAKE EXCITATION:

Ground motion selection and modelling method:

The SDOF model is subject to 20 ground motions for a model using a linear viscous damper as the supplemental damping system. The set of ground motions was selected for a general site in Christchurch, New Zealand with subsoil class D and an occurrence possibility of 2% in 50 years by Yeow *et al*. [2018]. Stiffness ratios of K_s/K_d = 1, 1.5, 5, 10 and 200 are selected. The inherent system damping is set at 5% of critical and the supplemental damping is defined so that the analysis is undertaken for a range of total system damping ratio from 5% to 35%, representing 0% to 30% supplement damping contributed by the viscous damper. Structural periods, T_n, of 0.25, 0.5, 0.75, 1, 2, and 3 seconds are considered.

For each ground motion simulation, the initial step is to identify the elastic spectral displacement demand at 5% damping, S_d, and spectral acceleration, S_a, at the period of the system for the selected ground motion. The next step is to input a supplemental damping constant, C_d, value into the model in OpenSEES to run the time-history analysis at a selected stiffness ratio and structural period. The input C_d value can be converted into an equivalent damping ratio using Equation (2).

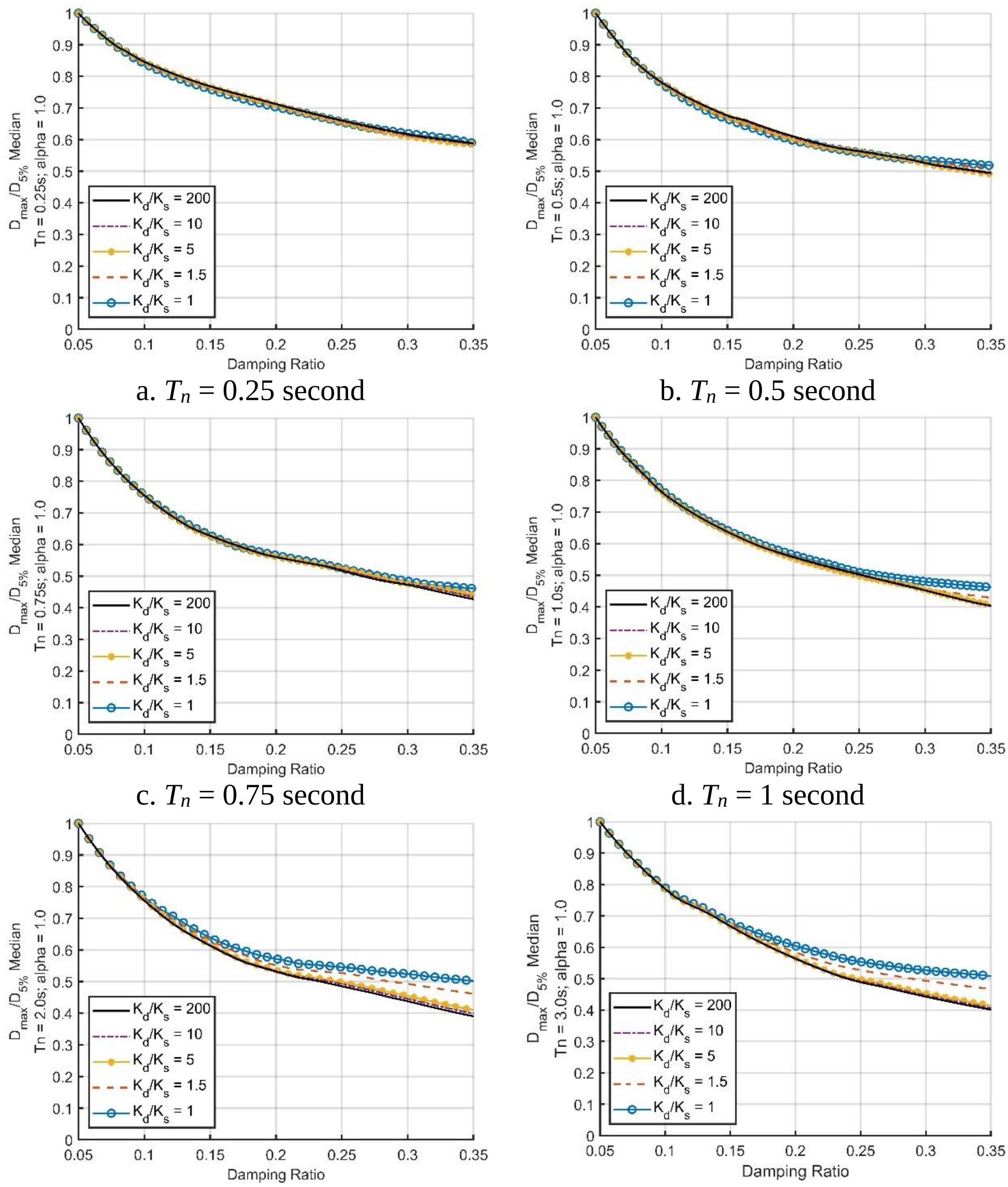
$$\zeta = (T_n C_d)/(4\pi M) \tag{2}$$

For each time-history analysis, the lateral displacement of node 2, and the reaction force of node 1 are recorded. The node 1 reaction force can also be referred to as the base shear force of the overall system. It is the sum of the instantaneous structural system forces, inherent damping forces, and forces from the supplemental damping system.

To present the results, at each damping ratio, the maximum absolute displacement, X_0, and base shear force, V_b, are extracted from the time-history data. These two values are normalised using the 5% spectral responses, S_d and S_aM, respectively. For the following sections of this paper, the normalised displacement, X_0/S_d, is defined as the displacement reduction factor (DRF) and the normalised base shear, V_b/S_aM, is defined as the base shear reduction factor (BSRF). Once simulations are completed for all 20 ground motions, the median value is identified and plotted against total damping ratio.

Displacement results

Using the modelling procedure described above, the median DRF-damping ratio curves obtained for the six selected structural periods are plotted in Figure 3. It can be seen that for a system possessing linear viscous dampers, the response is not sensitive to the change of stiffness ratio (SR) for structural periods less than 1 second.



a. T_n = 0.25 second

b. T_n = 0.5 second

c. T_n = 0.75 second

d. T_n = 1 second

e. T_n = 2 seconds

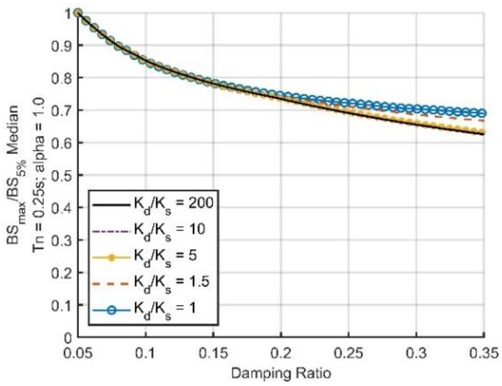
f. T_n = 3 seconds

Figure 3. Median DRF-damping ratio curves for linear viscous dampers, at the selected structural periods

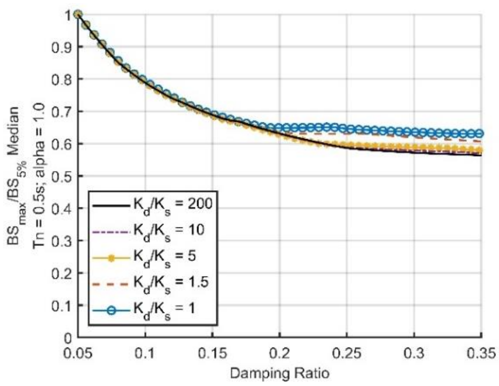
At T_n = 1 second, differences in DRF between SR = 1 and 200 become noticeable only for total damping ratios higher than 25%. For T_n = 2 and 3 seconds, the curves for SR = 1 and 1.5 start to show significant variation across different SRs above 15% damping, and differences in the DRF increase with increases in damping. It is also noted from the results that for all the selected periods, if the SR is greater than 5, the deviations from the high rigidity SR = 200 case in terms of displacement response are less than 5%, suggesting that this stiffness ratio could be a suitable target for design.

Total system force results

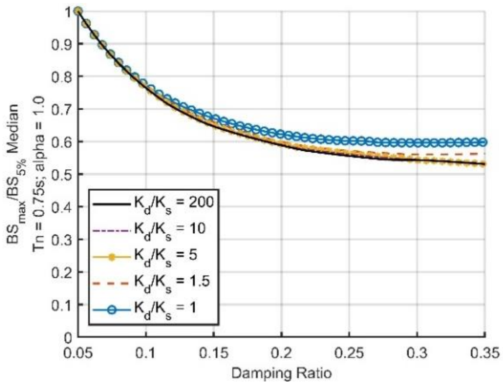
The median BSRF-damping ratio curves for the six selected structural periods are plotted in Figure 4. Unlike the displacement response, differences in BSRF between low and high stiffness ratios exist even at low periods such as T_n = 0.2s and become quite significant for periods longer than 0.75s. Figures 4d, e, and f show that, for the cases of SR = 1 and 1.5, the base shear response starts to show large variation across different stiffness levels for damping ratios higher than 10%. In Figures 4e and 4f, even for high stiffness cases of SR = 5 and 10, there are difference of up to 10% in BSRF between them and the SR = 200 case.



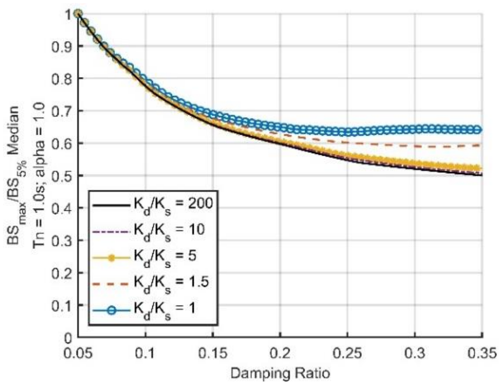
a. T_n = 0.25 second



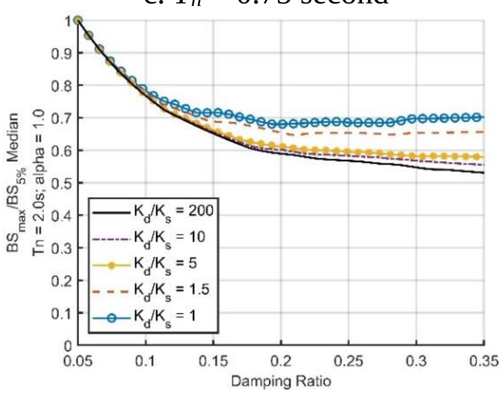
b. T_n = 0.5 second



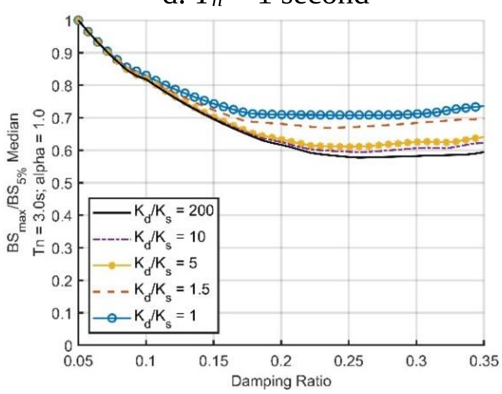
c. T_n = 0.75 second



d. T_n = 1 second



e. T_n = 2 seconds



f. T_n = 3 seconds

Figure 4. Median BSRF-damping ratio curves for linear viscous dampers

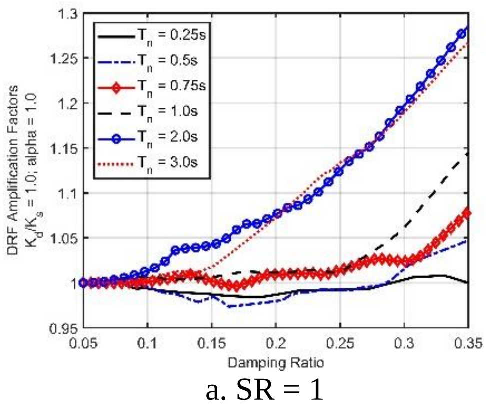
Although viscous dampers are designed to limit structural displacement, it is important to acknowledge the variations in base shear due to sub-system flexibility because this should be considered in capacity design when verifying foundations, connections and other parts of the lateral load resisting system. Based on the results obtained, it would appear that if the damper sub-system stiffness is equal to that of the structural system, the total reaction forces transmitted to the foundation may increase by up to 33%.

This increase is partially attributed to the fact that the damper and structure displacement response will be partially out-of-phase due to the influence of damper sub-system stiffness. The out-of-phase in displacement response leads to the response force for the damper and structure becoming more in-phase and leading to larger total reaction forces.

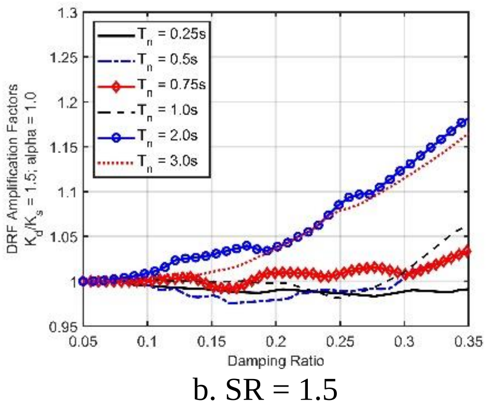
DESIGN RECOMMENDATIONS

This work has shown that in general, by ignoring the sub-system stiffness in the design process the effectiveness of the viscous dampers may be overestimated and the base shear demand may be underestimated. Both deviations from the design assumptions are non-conservative and warrant further consideration. To provide a better and clearer understanding of the results, the DRF amplification factors can be plotted by normalising the DRF for the stiffness ratio cases of 1, 1.5, 5, and 10 to the DRF of the near-rigid case (SR = 200). By doing so, the differences in displacement response between the high stiffness case (SR = 200) and the low stiffness cases can be quantified.

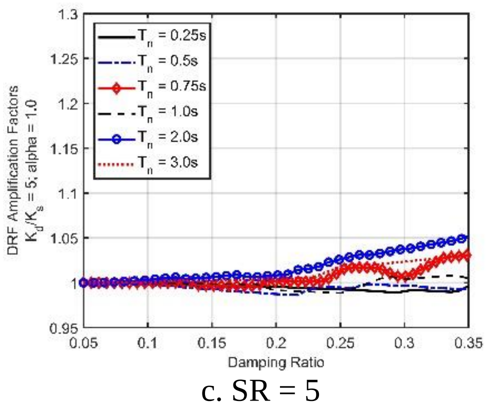
The resulting response amplification factors essentially represent a variation in response from the rigid-connection assumption often applied in design. To present this information, the DRF amplification factors are grouped by stiffness ratio (SR) and results for T_n = 0.25, 0.5, 0.75, 1, 2 and 3 are plotted together. Figure 5 shows the DRF amplification factors for the linear viscous damper system for SR = 1, 1.5, and 5.



a. SR = 1



b. SR = 1.5



c. SR = 5

Figure 5. DRF amplification factors at various structural periods, at SR = 1, 1.5 and 5

For the linear damper system, the peak DRF amplification factors for structural periods 0.5s and above reduce significantly as the stiffness ratio increases from 1 to 1.5 and to 5. At SR = 5, the highest DRF amplification factor for all stiffness cases are below 1.05, which indicates when a sub-system flexibility at this level is introduced, the overall system displacement response is amplified by no larger than 5%. The higher stiffness ratio reduces the sensitivity of the results to small changes in the damper sub-system flexibility. Therefore, as expected, stiffer damper connections which lead to stiffer damper sub-systems and higher stiffness ratios, lead to improved structural response.

This initial analysis has investigated the influence of sub-system flexibility when providing supplemental damping through the use of linear viscous dampers. An important extension of this work is to also consider the influence that damper sub-system stiffness may have when the supplemental damping is instead provided through the use of non-linear viscous dampers. This additional analysis is the focus of ongoing research.

CONCLUSIONS

This paper has described numerical investigations aimed at quantifying the extent to which the damper sub-system stiffness can affect the overall displacement response and total base shear force for a structural system subject to earthquake excitation. Results from ground motion simulations indicate that if the sub-system stiffness is less than 10 times the stiffness of the main lateral load resisting system, the overall system response can be significantly affected by the sub-system flexibility. Results from ground motion simulations show that at stiffness ratios (i.e. the damper sub-system stiffness to total structural stiffness) K_d/K_s = 1, 1.5, and 5, both the median peak displacement response and the total system force can be 5% to 33% higher than the response of a damper system with a stiffness ratio of 200.

The ground motion simulation results also lead to the recommendation that designers take sub-system flexibility into consideration if more than 5% supplemental damping is to be introduced to the structural system. By plotting the DRF amplification factors for different structural periods at various stiffness ratios, it is recommended that for structures with natural periods larger than 0.5s, the linear viscous damper sub-system be provided with a stiffness that is five times greater than the structural stiffness.

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