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The effectiveness of linear viscous damper and damper subsystem stiffness on response reduction in SDOF system subjected to different ground motions.

Indeed, bracing systems and viscous damper installations are both employed to mitigate structural damage produced by seismic actions. Bracing systems provide the structure with more rigidity and strength, while viscous dampers dissipate energy through fluid friction. The system can be made more resilient to potential damage by combining these two seismic design strategies. This paper investigates the effectiveness of viscous damper subsystem flexibility in reducing seismic responses to various ground motions. This study employs time history analyses with OpenSEES codes to calculate the optimal linear damper subsystem stiffness and viscous damper subsystem stiffness in SDOF systems based on different ground motions. The research explores the relationship between response reduction and peak ground acceleration for optimal viscous damper subsystem flexibility. The results demonstrate that seismic responses can be significantly reduced by 40% to 60% using viscous damper subsystem stiffness, which is nearly five times the inherent stiffness of an SDOF system. The findings of this research reveal an overall reduction in seismic responses in major earthquakes compared to moderate earthquakes. These findings offer valuable insights into the appropriate use of damper-brace stiffness, linear, or nonlinear viscous dampers in multi-degree-of-freedom (MDOF) systems, particularly for damper placement and retrofitting strategies.

Keywords: ground motion, response reduction, subsystem stiffness, viscous damper.

1 Introduction

To mitigate the devastating impact of earthquakes, structural engineering communities have developed innovative techniques and designs for constructing earthquake-resistant strategies such as moment-resisting, shear-resisting, braced, and dual frames. The components of these earthquake-resisting structures are being critically designed for disaster preparedness and mitigation efforts (Celik & Bruneau, 2009; Eng et al., 2011; Paulay, 1986). The configuration and design concepts of these structures are specifically intended to effectively dissipate seismic energy, thereby protecting people's lives and property. Although earthquake-resistant structures offer greater stability and strength, they do not lack limitations and challenges when it comes to properly maintaining the elastic ranges in the event of major quakes (Miranda & Bertero, 1994). The challenges associated with accommodating large sections of structural components could cause problems in terms of construction cost, aesthetics, constructability, and overloading the foundation. Hence, the implementation of an alternate technique becomes crucial for structures beyond the elastic range in regions prone to high seismic events (Losanno et al., 2017). Among the variety of energy dissipation devices, viscous dampers have emerged as a critical answer to the issues of excessive seismic energy that cannot be overcome by the earthquake-resistant structures abovementioned (Abdi et al., 2016; Liu et al., 2023; Mcnamara & Taylor, 2003). These outstanding technologies work by absorbing and changing seismic energy into heat, thereby protecting a building's structural integrity (Kim et al., 2003; Oinam et al., 2014; Seo et al., 2014). Numerous real-world applications have demonstrated the efficacy of viscous dampers in seismic energy dissipation (Infanti et al., 2008). Analytical investigations offer a theoretical foundation for understanding the behaviour of structures equipped with viscous dampers in the form of mathematical models and computer simulations. These analytical tools enable researchers to analyse the dynamic response of buildings subjected to seismic forces (Hejazi et al., 2014; Mansoori & Moghadam, 2009; Patel & Jangid, 2014). These studies provide valuable insights into the mechanisms of energy dissipation and the potential reduction of seismic damage. Researchers have also conducted numerous investigations in laboratory settings to investigate the characteristics of viscous dampers (Constantinou et al., 1993; Fan et al., 2004; Hwang et al., 2006; Zhang et al., 2023). Researchers used shake table tests to simulate earthquakes and observe how buildings with viscous dampers behaved (Hwang et al., 2006). The results of these experiments not only support the theoretical concepts but also show how dampers and other structural components interact. For example, viscous dampers work optimally when installed in the bracing systems; together, the brace-damper configuration reduces structural responses (Aydin & Boduroglu, 2008; Feng et al., 2021; Li-hua et al., 2019; Pourzangbar et al., 2020). The braces and incorporated viscous dampers absorb an enormous amount of energy and reduce structure forces, and this mechanism lowers damage and enhances performance. In a recent study conducted by Xie et al. (2021) the researchers examined the effects of a damper subsystem on reducing structural responses in SDOF systems. The findings of this study demonstrated the efficacy of this approach, highlighting its importance as a technique for reducing structural responses. The research investigation focused on SDOF systems characterised by natural periods spanning from 0.25 to 3 seconds. They employed a collection of ground motions derived from the seismic activity of the Christchurch earthquake. An interesting point has been made in their observation: they found that the optimal amount of damper subsystem stiffness should be five times higher than the inherent system stiffness, and brace flexibility may occur if damper subsystem stiffness is almost as high as the inherent stiffness. A deeper understanding of these observations is required to investigate the exact amount of stiffness ratio of the damper subsystem, determine response reductions in the SDOF system having a longer natural period, and compare the response reductions for different earthquake actions. Expanding upon previous research, the present study investigates the subject matter by examining longer natural periods (specifically, Tn = 4 and Tn = 5 seconds) as a means of representing high-rise buildings. In addition, the research incorporates seismic activities from the Kahramanmaras earthquakes in Turkey, encompassing ground motions generated by sources located in near, medium, and far-field station databases. The primary objective of this extension is to enhance the comprehension of the damper subsystem's performance in a wide range of scenarios. This will contribute to a more thorough evaluation of its effectiveness in different seismic conditions. This work is, however, useful to give us an idea of the necessity of inserting viscous dampers and the optimal amount of supporting brace dampers for near-field ground excitations.

1.1 SDOF system and subsystem damper configuration

This research followed the framework proposed by Xie et al. (2021) and modelled (SDOF) in OpenSEES. An arrangement of a system with two nodes, one fixed and one free to undergo deformation, is shown in Figure 1. A deformed node has a mass of 1,000 tonnes. Furthermore, the system incorporates three uniaxial, zero-length elements. The middle element constitutes a linear elastic spring, which functions as the mechanism for resisting lateral forces. This spring is connected in parallel with a viscous dashpot, which contributes to the inherent damping force of the system. In addition, the third element can be characterised as a Maxwell model that is placed in parallel with the other two elements. This subsystem consists of a viscous dashpot of a supplemental damper connected in series with an elastic spring that represents the stiffness of the subsystem (the supporting brace). The damping coefficient for the supplemental dashpot is denoted as Cd, while Ci stands for the inherent damping coefficient of the main system. The linear elastic subsystem stiffness which refers to the total stiffness of system supporting damper including bracing member and its supports is represented by Kd whereas Ki symbolises the inherent stiffness of the system. This setup represents both the main system (forming the structural frame) and the damper subsystem (consisting of a viscous damper and the stiffness of the brace supporting the damper).

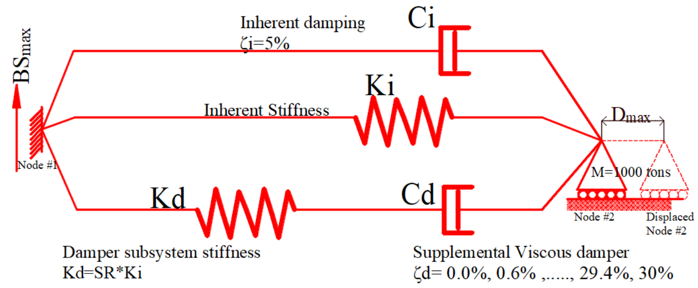

Figure 1. SDOF system and damper subsystem.

2 Efficacy of damper sub-system flexibility on structural response to pulse excitation:

The analytical approach used three different arrangements that are oscillated by pulse excitation to find out if there was a relationship between the damped frequencies with respect to the stiffness of the damper subsystems. The SDOF systems under consideration include three cases: inherent system ξ_i = 5% with no supplemental damper and subsystems, inherent system ξ_i = 5% with a damper subsystem stiffness ratio (SR = 1) and ξ_d = 30%, and inherent system ξ_i = 5% with a stiff subsystem stiffness ratio (SR = 200) and ξ_d = 30%. Based on the information in Figure 2, the flexible subsystem's damped period (1.066 seconds) is longer than the inherent system's natural period (1.0 sec). On the other hand, the observation is reversed when examining a stiff subsystem (0.85 seconds). It has been revealed that the damped frequency of the flexible subsystem exhibits a decrease compared to the bare system when the supplemental damping coefficients are increased. The phenomenon described can be linked to the brace's flexibility, as observed in the study conducted by Xie et al. (2021).

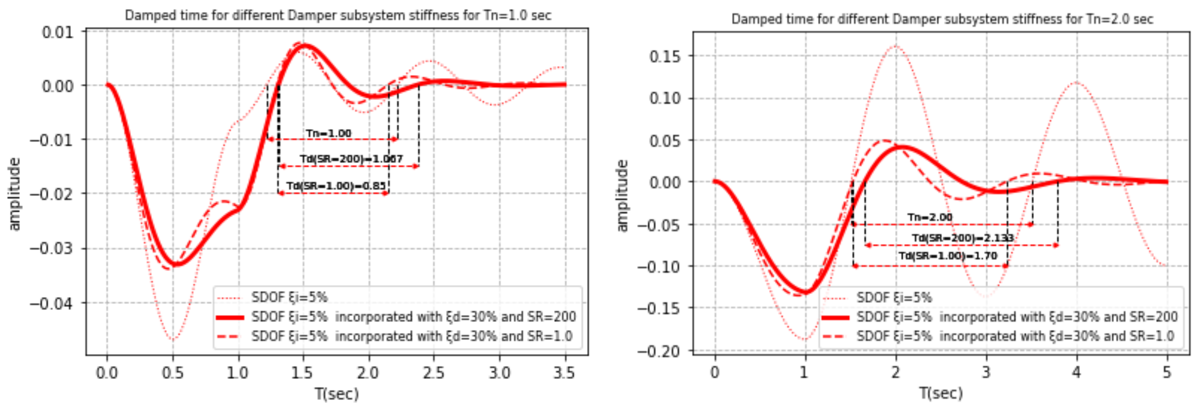

Figure 2. The damped time calculation for three different SDOF systems

A framework developed by a previous study is followed to consider the relationship between damper subsystem stiffness and damped frequency. This was calculated as described in Equation 1. The principle in the equation is based on the concept of balancing the energy dissipated by a linear viscous damper with the strain energy (Lin et al., 2008).

$$\xi_d = \frac{T.C_d}{4\pi M_s} \qquad 1)$$

Where ξ_d is damped ratio of viscous damper, T is natural period, C_d damped coefficient, M_s is the mass of the SDOF system.

To provide a comprehensive analysis, this study extends upon and examines different arrangements under pulse excitation with natural periods of 1.0 and 2.0 seconds. The range of subsystem stiffness ratios considered spans from an extremely flexible subsystem with a ratio of SR = 0.0 to a rigid subsystem with SR = 200.0. Additionally, the total damping ratio, which includes both the inherent damping ratio and the supplemental damping ratio, varies from 5% to 35%. The results obtained from the analysis showed that a stiffness ratio SR equal to 5 or higher approximately exhibits the same behaviour as the rigid system. The damped natural frequency obtained from the analytical solution, as represented by Equation 2, closely approximates the damped frequency of the highly rigid subsystem resulting from OpenSEES. The introduction of error occurs when the model deviates from the underlying assumptions due to a decrease in the stiffness of the damper subsystem.

$$\omega_d = \omega_n \sqrt{1 - \xi_d^2} \quad 2)$$

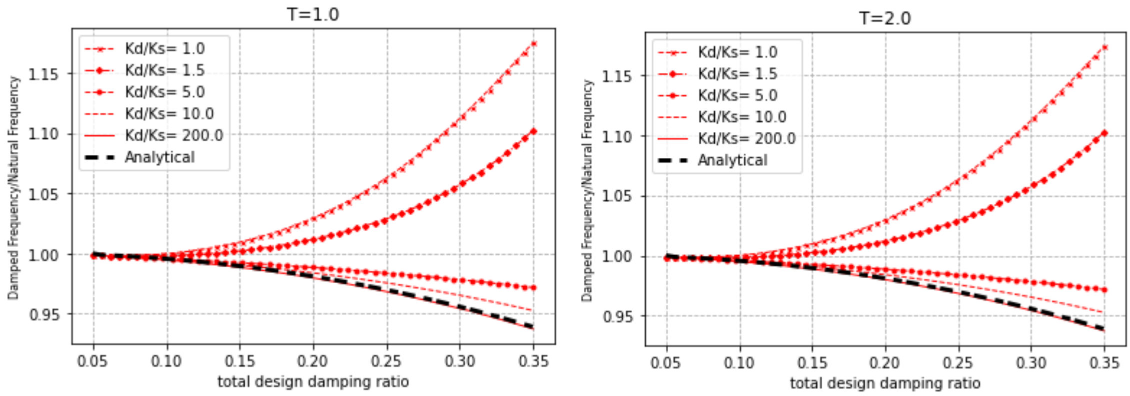

Figure 3. Damped frequency/ natural frequency and total damping ratio.

Referring to Figure 4, the subsystem damper and the system display out-of-phase from SR = 0 to SR = 3, commonly referred to as brace flexibility. The damped frequency achieves its maximum value when the damping ratio (SR) reaches 1.2. Afterwards, at SR greater than 3.0, there is a gradual decrease in the damped frequency until the subsystem reaches a level of high stiffness. Based on the observations, it is recommended that the system reliability (SR) not be less than 3.0.

$$K_i = \omega_n^2 * Ms \quad 3)$$

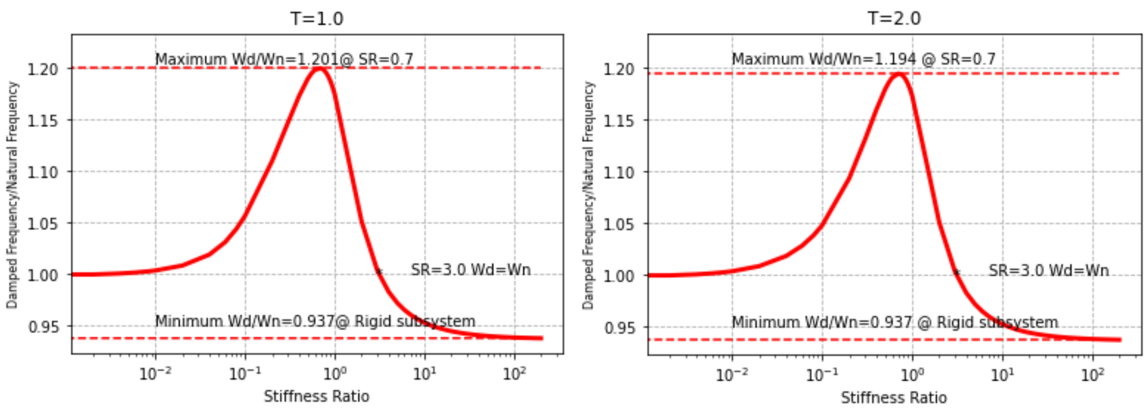

Figure 4. Brace flexibility and damped frequency/ natural frequency.

3 Impact of Sub-System Flexibility on Response Reduction to Earthquake Excitation Linear viscous damper

Twenty ground motions with the highest peak ground acceleration were chosen to study how linear viscous dampers and subsystem stiffness affect the reduction of seismic response for SDOF systems. These ground motion records were selected specifically from the seismic activity that occurred during the 2011 Christchurch, New Zealand, earthquake(The PEER Center). The recommended damper subsystem stiffness ratios (SR) are.0, 1.5, 5.0, 10.0, and

200.0 times the inherent stiffness. An investigation was conducted on supplemental damping ratios ranging from 0% to 30% for each of the stiffness ratios. During the examination, an incremental ratio of 0.6% was added to the existing inherent damping ratio of 5%. The present arrangement has been specifically devised to accommodate natural periods of 0.25, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0. The scope of buildings examined in this study encompasses a variety of structures, ranging from low-rise to high-rise. The primary objective of this investigation is to assess the effects of the damper subsystem.

The direct time integration Newmark method with parameters ϒ = 0.5 and β = 0.25 is employed to conduct a time history analysis for each SDOF system characterized by different natural periods in OpenSEES software. The time intervals are assumed to be 0.05 seconds, and the number of points is derived from ground motion records. In the first step, the natural frequency is determined by the natural period of the SDOF system. Furthermore, the determination of the inherent damping coefficient is based on a mass of 1000 tonnes and an inherent damping ratio of 5%, as specified by Equation 1. The current dataset is employed to determine the maximum displacement (D5%) and maximum base shear (BS5%) in an SDOF system without the inclusion of supplementary damper installations. The absolute displacements depicted in Figure 4 are used to normalise the displacements resulting from the insertion of a damper and subsystem stiffness.

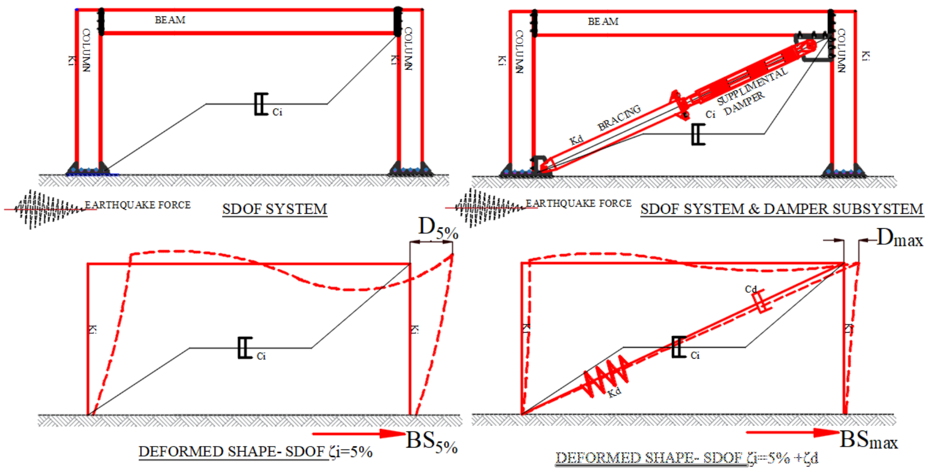

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Figure 4. Maximum displacement in SDOF system with and without damper subsystem.

The following procedure includes the calculation of the damped frequency, which is determined based on the given information on the combined total supplemental damping ratio, which represents the combination of the inherent damping ratio and the supplemental damping ratio. The damped frequencies are employed to determine the supplemental damping coefficient for the highly flexible damper subsystem, while the natural frequency is utilised for the stiff damper subsystem. The maximum absolute displacement (Dmax) at node 1 and the maximum absolute base shear (BSmax) at node 2 are calculated by a time history analysis for each setup. The data are normalised with respect to the maximum displacement (D5%) and base shear (BS5%). Fundamental parameters are the normalised displacement (DRF = Dmax / D5%) and base shear (BSRF= BSmax /BS5%). The determination of the median value is based on the execution of all ground motions with simplified design damping ratios which is the total of designed damped coefficient of the damper ξd=30% and the inherent damping ratio of the system ξi=5% .

The findings indicated an important correlation between the reduction in displacement and the gradual increase in the total damping ratio throughout all-natural periods. The effectiveness of subsystem stiffness in reducing structural responses is found to be inadequate for durations periods less than 1.0 seconds. Nevertheless, it exhibits efficacy over long periods (Tn > 2 seconds). The findings presented in this study align with previous research, indicating that the impact of the subsystem becomes evident when the overall damping coefficient exceeds 20%. When the subsystem stiffness ratio reaches a value of SR = 5, the performance becomes nearly identical to that of the subsystem equipped with a rigid damper.

There is a big difference in the amount of displacement that can be reduced between a stiffness ratio of 1.0 and 5.0 in SDOF with a structural time of more than 1.0 seconds. These findings may emphasise the importance of damper subsystem stiffness for high-rise buildings in high-seismic areas. An additional noteworthy observation is that the stiffness of the damper subsystem, ranging from 5.0 to 10.0, demonstrates almost equivalent characteristics to those of a rigid damper. This observation is consistent with the findings reported by Xie et al. (2022). The result shows a significant rise in displacement reduction from 0.25 seconds to 3.0 seconds, from 50% to 60%. It is, however, seen from Figure 4 that the maximum value of the reduction in displacement is below 50% between T = 4.0 and 5.0 seconds. One of the key findings highlights the importance of the stiffness of the damper subsystem as well as a characteristic of the viscous damper. The observed results may be influenced by many factors, including frequency contents, peak ground acceleration, quantity of data points, and ground motion time interval.

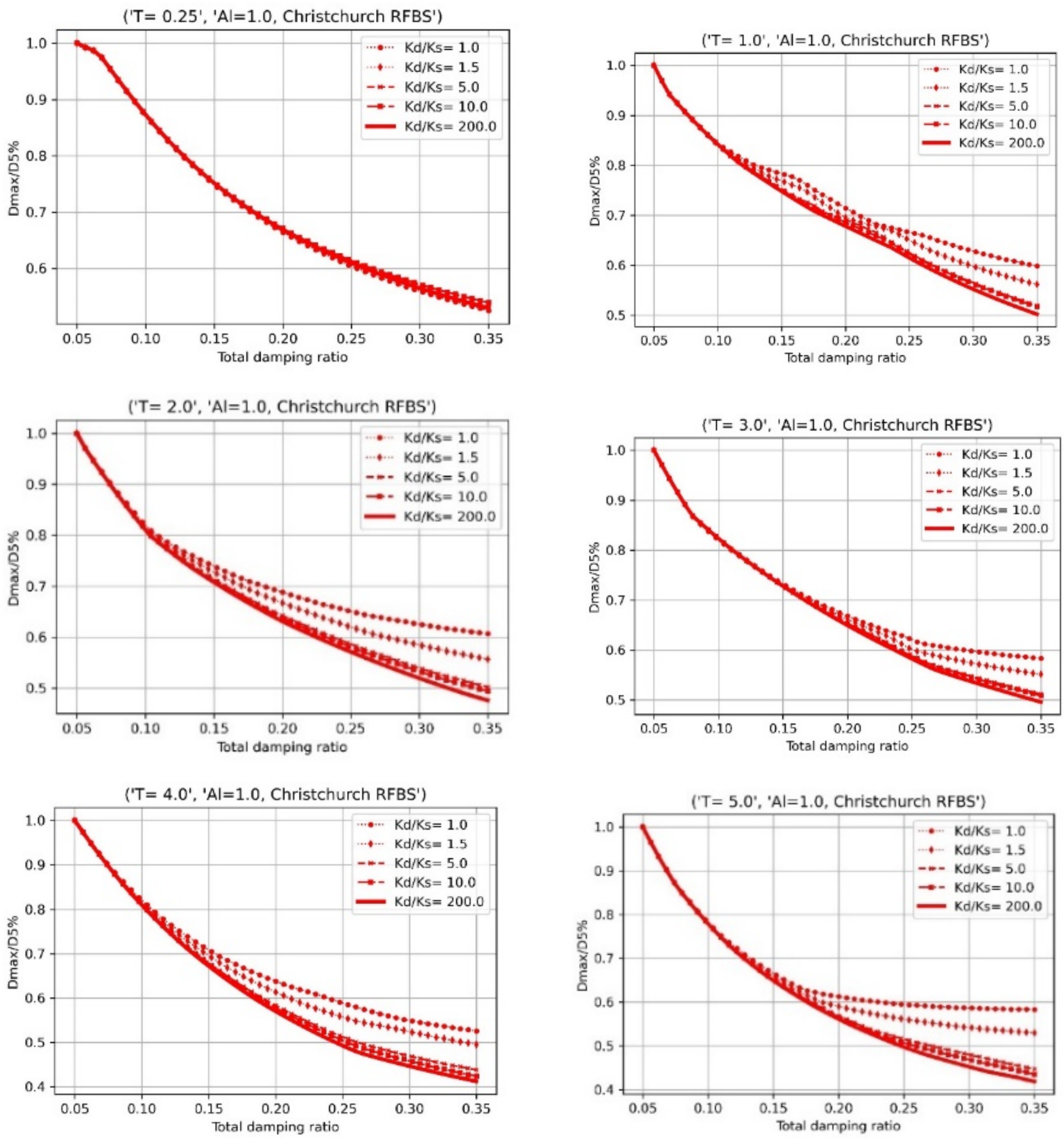

Figure 4. Maximum displacement in the SDOF system for a natural period spanning from 0.25 to 5.0 seconds.

Figure 5 illustrates the relationship between the reduced base shear, the total damping ratio, and the subsystem stiffness of the supplemental dampers. The effect of the damping ratio and the stiffness of the damper subsystem on the reduction in base shear is seen in the same way as the reduction in displacement. Nevertheless, the impact of increases in subsystem stiffness becomes evident at an exact time of 0.5 seconds. Once the stiffness ratio of the damper subsystem exceeds the limit of SR = 5, it exhibits characteristics almost similar to those of a rigid subsystem with a stiffness ratio of SR = 200. In systems characterised by a natural period exceeding 1.0 seconds, it has been observed that a 15% decrease in the base shear can be attained by increasing the stiffness ratio of the subsystem from SR = 1 to SR = 5. Based on time history analysis, it is impossible to predict how highly flexible subsystems help reduce base shear for structural periods longer than 2.0 seconds. Prior research has examined this matter in the context of a structural time of 3.0 seconds(Xie et al., 2022). The long periods of natural period T = 4.0 and 5.0 seconds fulfil the purpose of emphasising this observation. Notable differences arise between the system and damper subsystem as the natural periods increase, particularly when the damping ratio has a 27% increase. Both flexible and rigid subsystems will exhibit considerable out-of-phase characteristics.

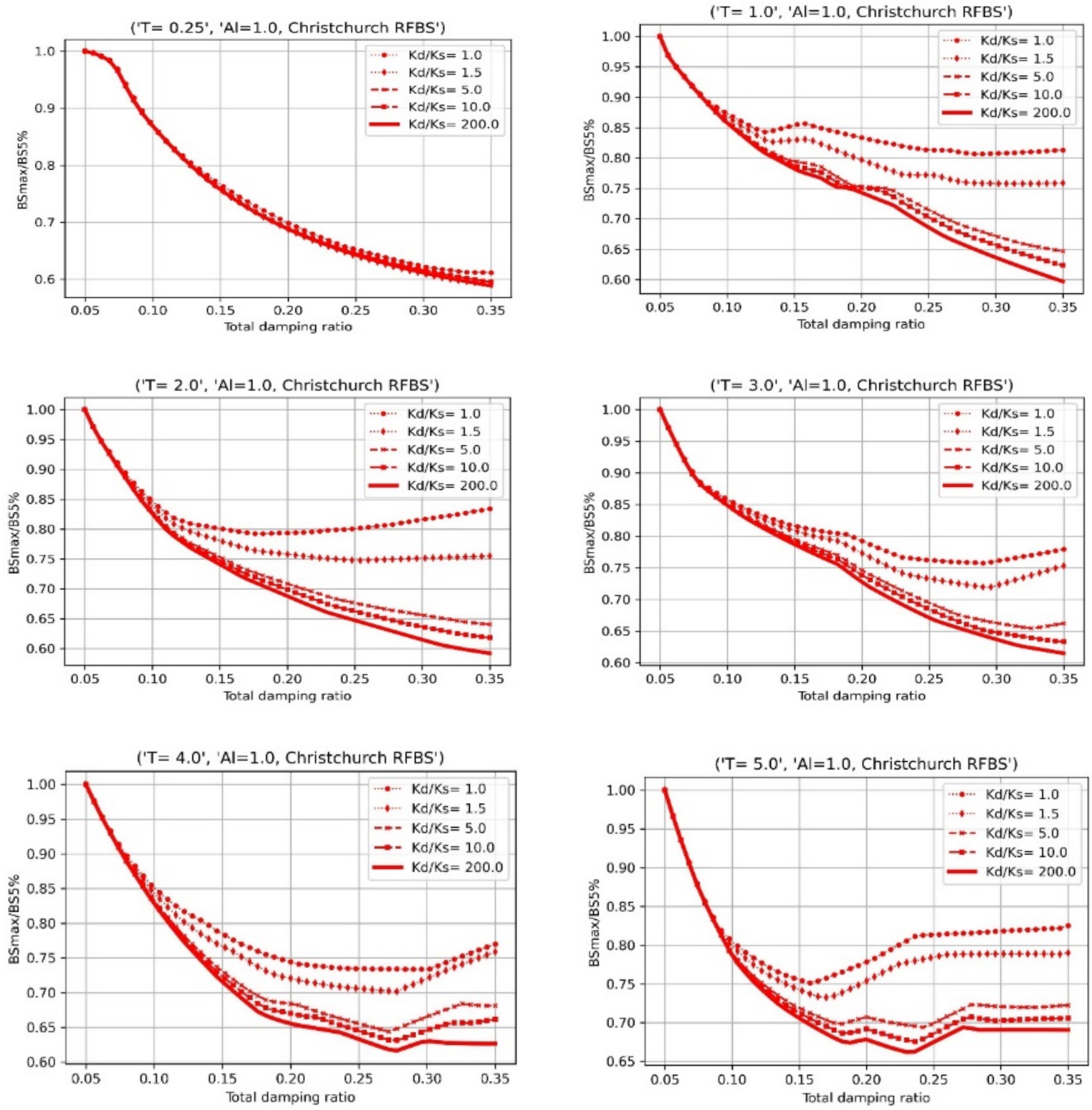

Figure 5. Maximum base shear in SDOF system for a Period spanning from 0.25 to 5.0 seconds.

4 Comparison in Response Reduction between Far-field, Medium-field, and Near-field excitations of the 2023 Kahramanmaras, Turkey Earthquake.

On February 6, 2023, central and southern Turkey experienced two seismic events with magnitudes of 7.8 and 7.7 on the Richter scale, resulting in a significant loss of human life, with an estimated death toll of over 40,000 individuals. The seismic activity resulted in significant structural damage and destruction (Jia et al., 2023). To facilitate the objectives of this research, the subsequent ground motion data were obtained by extracting records from the (AFAD) database. To investigate the efficacy of the stiffness of the viscous damper subsystem, three distinct sets of ground motion data are analysed. These sets include far-field excitations at a median distance of 612.22km from the epicentre, medium-field excitations at 121.95km, and near-field excitations at 32.65km. Figures 6 and 7 depict the results of a comprehensive analysis that specifically examines the response of the damper subsystem stiffness to different seismic events. The findings highlight the negligible influence of damper subsystem stiffness on SDOF systems exposed to far-field earthquakes. Specifically, the maximum displacements of SDOF systems with natural periods ranging from 0.25 seconds to 5 seconds are not significantly altered. This observation highlights the insignificant importance of implementing dampers and considering subsystem flexibility for structures located farther away from the epicentre.

More importantly, the figures present a stark contrast for near-field earthquakes, where the significance of damper subsystem stiffness is pronounced. In these instances, displacement reduction reaches a remarkable 50%, highlighting the crucial role that this system component plays in enhancing structural resilience under such seismic conditions. For a system with Tn = 1, its displacement can be reduced from almost 12 mm to around 7mm. Likewise, for T = 5.0 seconds, the maximum displacement is approximately 600mm by adding a viscous damper, and subsystem stiffness drops to nearly 300 (about a 55% reduction as seen in Figure 7). However, a notable shift occurs when considering structural times exceeding 2 seconds in the context of medium-field earthquakes, reducing displacements from around 100mm to approximately 50mm for Tn = 5.0. Here, the effectiveness of the damper subsystem stiffness becomes apparent, demonstrating its potential to mitigate displacements significantly. Regarding the results of medium-field earthquakes, some interesting observations may be made for SDOF systems that have a natural period longer than 3 seconds and show a considerable reduction in displacement, as seen in Figure 7.

5 Conclusion

The findings of the current research align with previous research conducted by Xie et al. (2021). The results of the research suggest that it is crucial to ensure that the stiffness of the damper subsystem should not be less than three times higher than the lateral stiffness of the structure. Furthermore, it was noted that a stiffness ratio SR = 5 demonstrated comparable efficacy to that of a rigid subsystem stiffness. The observation was made regarding the importance of the stiffness of the damper subsystem in reducing responses, particularly in structures with longer natural periods. Research conducted on earthquakes in Karamanmaras, Turkey has revealed that the installation of a damper and damper subsystem is an efficient approach for minimising the seismic responses caused by near-field excitations. This conclusion was drawn from comparative analyses of earthquakes of varying magnitudes, including big, moderate, and small seismic events. The impact on the stiffness of the damper subsystem, however, is generally minimal when exposed to seismic events occurring at far-field from the structure. It is crucial to bear in mind that the damper subsystem mostly impacts structures characterised by longer natural periods when subjected to moderate-distance seismic events.

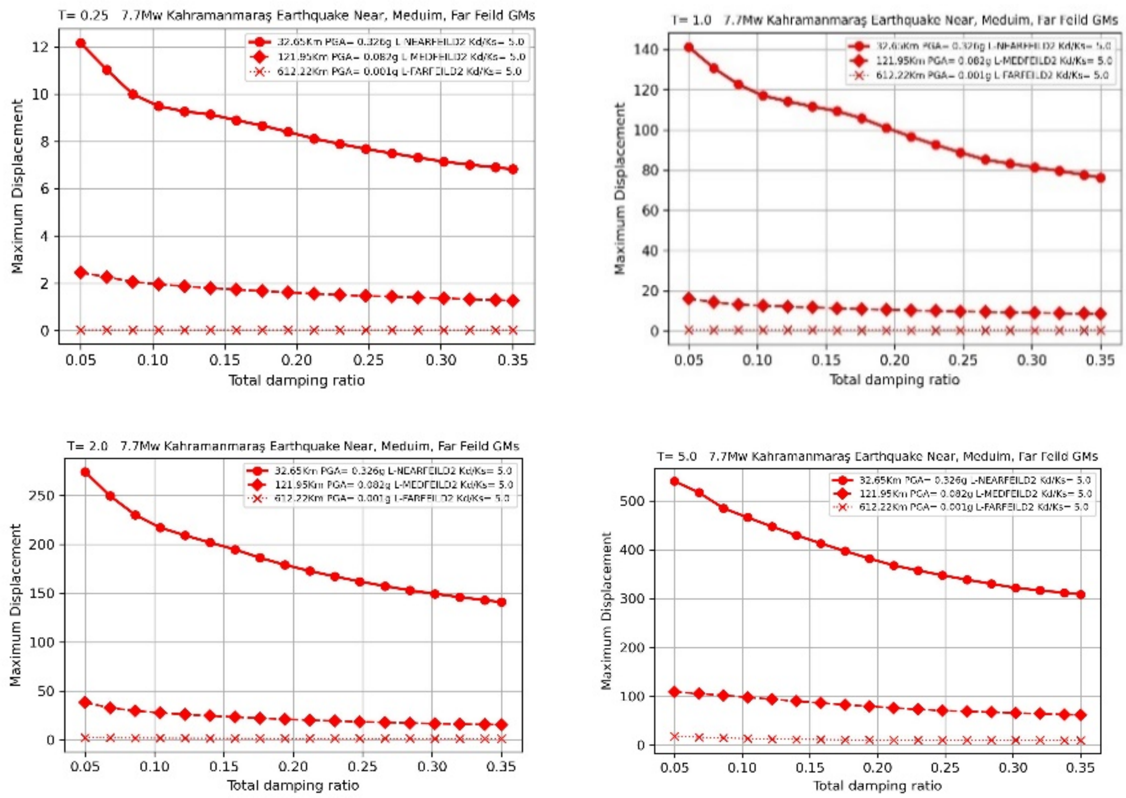

Figure 6. Dmax in SDOF system for a Period spanning from 0.25 to 5.0 seconds, Hatay Earthquake.

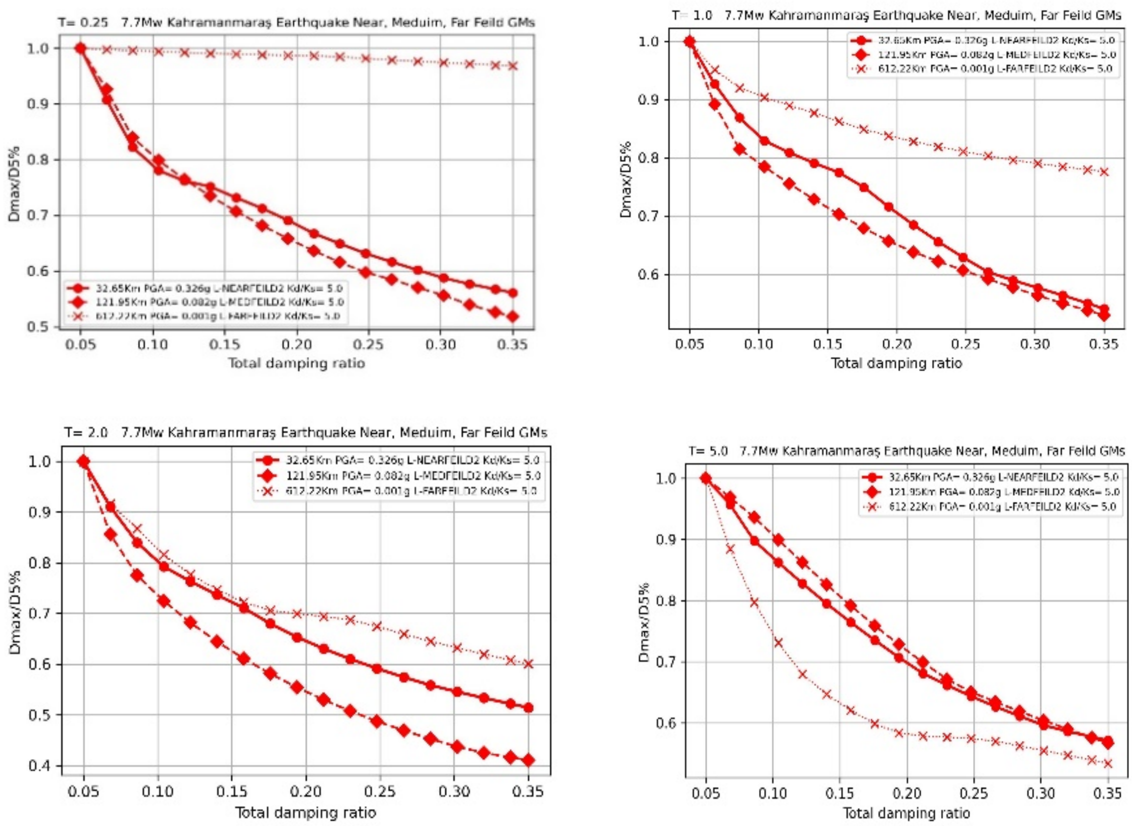

Figure 7. DRF in SDOF system for Time period spanning from 0.25 to 5.0 seconds, Hatay Earthquake.

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