Low-Initial-Stiffness Dampers for Improved Seismic Response

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SUMMARY:
The force-deformation curves for typical lateral force resisting systems have an initial elastic stiffness, a yield point, and some post-yield stiffness. This paper explores systems with dramatically different force-deformation curves: systems with relatively low initial stiffness that actually gain stiffness at larger displacements and remain elastic; final stiffness may be several times the initial stiffness. Dampers that exhibit this force-deformation response are called hyperelastic dampers. Results from time history analysis of single-degree-of-freedom models are used to demonstrate situations where hyperelastic dampers may provide superior seismic performance to traditional systems.

Keywords: dampers, response history analysis, structures

1. INTRODUCTION

Earthquakes and their associated effects present a significant challenge to structural engineers. Considerable time and resources have been spent over the years researching methods to mitigate the effects of earthquakes and reduce the amount of acceleration and displacement the structure experiences. Discovering ways to economically design structures to survive large earthquakes and remain operable with minimal repair is an important field of structural engineering research.

This study proposes a type of passive seismic control system involving dampers with unique hysteretic behavior. The dampers would be designed such that they would have little or no stiffness at low displacements and provide increasing stiffness as displacements increased. The theory being that initially "soft" dampers would increase the period of a structure in the same manner as base isolation systems and therefore decrease the seismic load on the structure. The dampers would then stiffen when required to elastically resist the load that does come. Because the system increases in stiffness with displacement, it is called a hyperelastic system.

A hyperelastic system could be created by a variety of methods, such as two different dampers in series, using rubber constrained in a steel cylinder, or even with magnets. The purpose of this study is not to develop a system that exhibits this behavior, but to investigate the dynamic response of such a system. The results of this study could help determine if further investigation into these types of systems is warranted.

2. BACKGROUND

The hyperelastic system being investigated might be classified as a braced frame because it could serve as the primary lateral force resisting system of the structure. However, it would exhibit properties of dampers, isolation systems, and self-centering systems as well. Therefore, previous studies on dampers, isolation systems, and self-centering systems are pertinent to this work.

2.1. Energy Dissipation Systems (Dampers)

Energy dissipation systems, commonly known as dampers, are a developing technology designed to improve the performance of inelastic systems. The primary purpose of dampers is to reduce the amount of energy dissipation required through the release of strain energy, which reduces the amount of inelastic deformation and damage to framing members (Constantinou and Symans, 1993). The proper implementation of dampers could limit the damage to a structure such that it could maintain functionality after a major earthquake.

Passive dampers are devices which use the relative displacement of the attachment points to produce control forces or dissipate energy. There are two types of passive dampers, rate-dependent and rate-independent (Symans et al., 2008). Rate-dependent dampers, as the name implies, resist load in proportion to the rate of change of displacement along the damper. Rate-independent dampers resist load in proportion to the magnitude, and possibly the direction, of the displacement along the damper, which is why they are also known as displacement-dependent dampers.

Marshall and Charney conducted an investigation of hybrid systems which combined a rate-dependent and a rate-independent damper (Marshall and Charney, 2011). Some of these configurations resulted in a hyperelastic system which increases in stiffness with displacement.

One of the more promising recent developments in seismic control is magnetorheological dampers. These dampers were demonstrated numerically by Dyke et al. to reduce the displacement of a three-story building model under a seismic load by about 30% (Dyke et al., 1996). They later verified their results experimentally with a scaled down model of the building on a shake table at the University of Notre Dame (Dyke et al., 1998). Xu et al. performed a parametric investigation of magnetorheological dampers in a five-story building model (Xu et al., 2000).

2.2. Base Isolation Systems

Another recognized seismic protection strategy is base isolation, which is the practice of disconnecting, or isolating, the structure from the foundation in order to increase the structure's flexibility.

Base isolation works by increasing the period of the base of the structure, filtering out high frequency ground motions. This makes base isolation especially effective for structures with short natural periods because they will only experience high period ground motions. However, for this same reason, structures with long natural periods are not benefited by base isolation. In fact, base isolators could make the response of long-period structures worse by filtering all ground motions except for those at the same period of the structure, causing resonance.

The most prevalent base isolation system incorporating sliding elements is the friction pendulum system. Zayas et al. performed a numerical study comparing the response of a three-story moment frame structure with and without a friction pendulum system (Zayas, 1990). Fenz et al. conducted exploration and testing of the behavior of a double concave friction pendulum system, which has a concave surface on each side of the bearing (Fenz and Constantinou, 2006). They found that this system is able to provide a greater displacement capacity than ordinary friction pendulum systems and has more parameters, making it more adaptable to specific applications.

Passive base isolation systems may be equipped with control actuators to create an active base isolation system with improved performance over a wider range of earthquakes. Chang et al. conducted an experimental study of a system comprised of a scaled three story building with computer controlled actuators on the shake table at the University of Illinois (Chang and Spencer, 2010). Bani-Hani and Sheban performed an analytical study of a five story structure with different types of base isolations systems (Bani-Hani and Sheban, 2006).

2.3. Self-Centering Systems

Traditional systems typically result in large residual displacements after a significant seismic event. Self-centering systems are attractive because they eliminate these residual displacements and return the structure to its original shape after an earthquake. The primary advantage of the proposed hyperelastic system, like self-centering systems, is the elimination of residual displacements.

Shape memory alloys used as self-centering systems in seismic applications were explored in a numerical investigation by Bruno et al. (Bruno and Valente, 2002). Another self-centering method, the use of post-tensioned energy dissipating devices, was explored by Christopoulos et al. (Christopoulos et al., 2002). Another system, comprised of steel braces interconnected by a friction energy dissipating device and equipped with pretensioned steel cables was investigated analytically by Tremblay et al. (Tremblay et al., 2008).

2.4. Sequential Coupling

A method of seismic control designed to reduce the cost of the seismic load resisting system and eliminate residual displacements know as sequential coupling was proposed by Paul Weidlinger (Weidlinger, 1996). Rather than dissipating energy or adding resistance like other seismic protection strategies, this system takes advantage of a specific property of oscillatory response, namely that "the amplitude of any local maximum response may be reduced if the amplitude of the immediately preceding local minimum is increased by reducing the yield resistance." A sequential coupling system accomplishes this with a series of elastoplastic systems. The objective of the present work is to show that hyperelastic dampers can provide the same advantage, but do so without the inelastic behavior found in the elastoplastic systems.

3. METHODS

The purpose of this investigation of the hyperelastic system was to observe its behavior in a single-degree-of-freedom (SDOF) model. This simple model allowed the comparison of its behavior against traditional systems and over a wide range of parameters.

3.1. Dynamic Analysis of a Hyperelastic Frame

The SDOF system for this analysis was modeled as shown in Figure 1. The columns and beam of the frame were modeled as truss elements and assigned an elastic material with very large cross-sectional area in order to isolate axial deformations to the brace. The stiffness of the system was controlled by modifying the cross-sectional area of the brace.

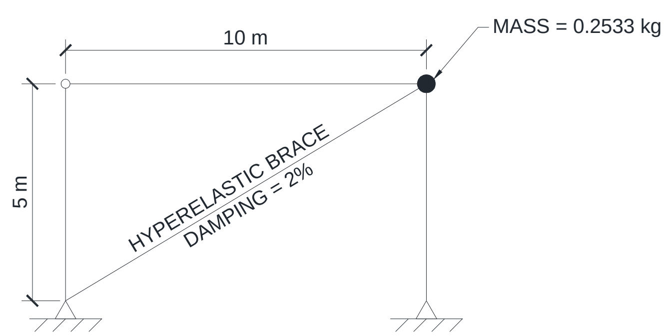

Figure 1. Frame model used in SDOF analysis

3.2. Modeling the Hyperelastic Damper

The hyperelastic device being explored was unique in its behavior because, unlike most materials which lose stiffness as displacements increase beyond the yield point, its stiffness increases after reaching a predetermined displacement. This behavior can be defined by three parameters: *k*, the final stiffness of the system; δ_y, the displacement at which the system increases stiffness; and α, the ratio of initial to final stiffness. These parameters are shown in Figure 2.

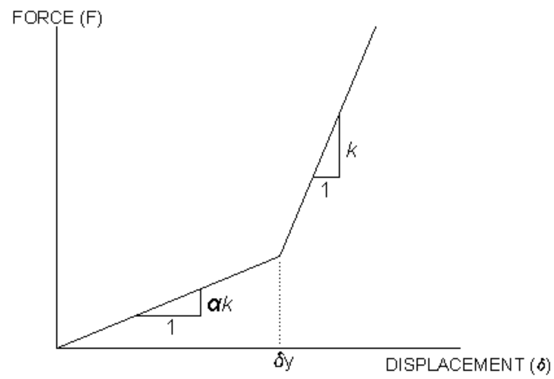

Figure 2. Parameters used to describe behavior of hyperelastic material

4. DYNAMIC ANALYSIS

In order to see general advantages and disadvantages of the hyperelastic system, the response of frames subjected to the 1940 El Centro acceleration time history (recorded at the Imperial Valley Irrigation District substation) are shown below. Figure 3 shows the response and hysteretic behavior of two SDOF systems, one with a hyperelastic brace and one with a traditional steel brace, both with a period of 1.0 second. The period of the hyperelastic system was determined using the final stiffness of the system.

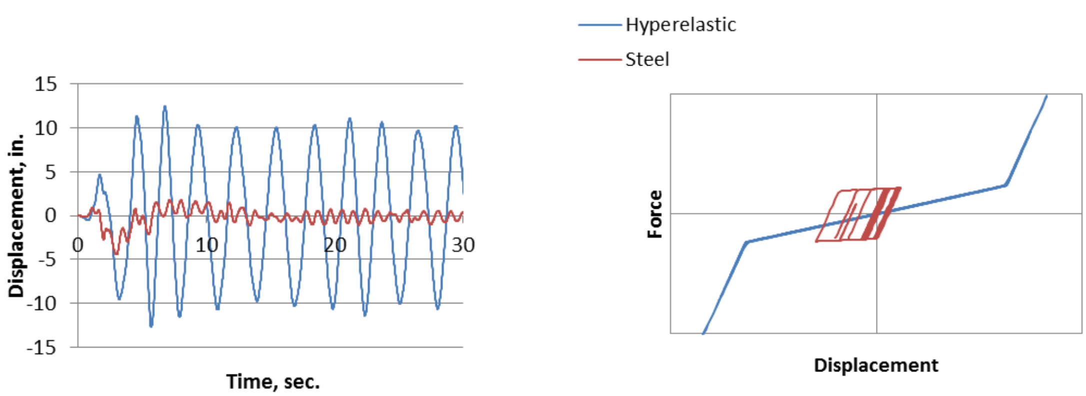

Figure 3. Displacement time history and hysteretic behavior of 1-sec period frames (δ_y = 8.5 in., α = 0.1)

The response of the 1-second period structure with the hyperelastic system experienced 290% of the displacement and 440% of the base shear of the structure with the steel brace. The reduction of residual displacement was only 3.5 inches. This is a small benefit relative to such a large increase in the response.

This is clearly an example where a hyperelastic damper performs worse than a traditional system. To contrast, figure 4 shows the response and hysteretic behavior of SDOF systems with a period of 4.0 seconds.

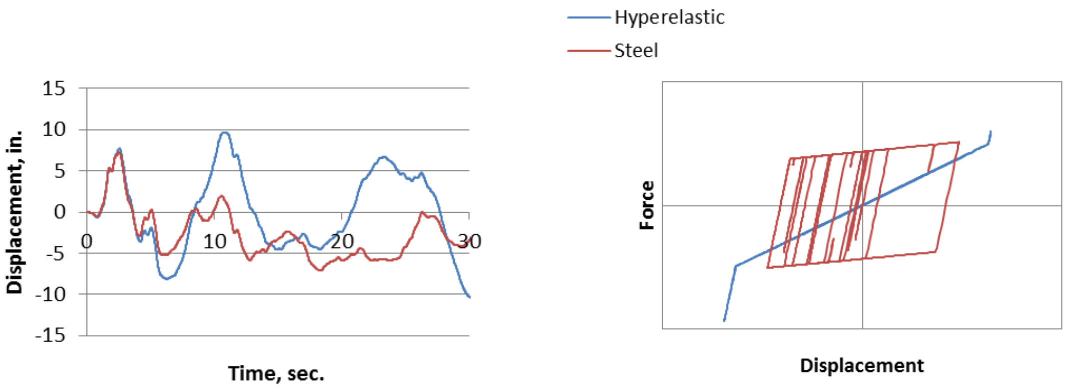

Figure 4. Displacement time history and hysteretic behavior of 4-sec period frames ($\delta_y = 8.5$ in., $\alpha = 0.1$)

The 4-second period structure with the hyperelastic system only experienced 140% of the displacement and 180% of the base shear of the structure with the steel brace while reducing the residual displacement by 6.2 inches. The significantly higher reduction in residual displacement could justify the smaller increase in response.

These results imply that hyperelastic systems may be advantageous for long period structures, where base isolation is less advantageous. A summary of relevant values from the plots can be found in Table 1.

Table 1. Response Values From the Frame Analysis

	1-second Period		**4-second period**	
	Hyperelastic	**Steel**	**Hyperelastic**	**Steel**
Maximum Displacement, cm (in.)	32.3 (12.7)	11.2 (4.4)	26.4 (10.4)	18.5 (7.3)
Maximum Base Shear, kN (kip)	179 (40.3)	40.9 (9.2)	4.89 (1.10)	2.67 (0.6)
Residual Displacement, cm (in.)	0 (0)	8.89 (3.5)	0 (0)	15.7 (6.2)

5. PARAMETRIC STUDY

The primary objective of the SDOF study was to determine the values for the three parameters of a hyperelastic system described above that result in an improved structural response to seismic loads. The parameters of the same SDOF system as in the previous section were altered over a range of values and analyzed under a suite of ground motions. The analysis produced the relative displacement and absolute acceleration spectra for each case. The parameters examined in this study incluce the stiffness, k, the displacement where stiffness increases, δ_y, the stiffness ratio, α, and the ground motions under which the system is analyzed.

5.1. Hyperelastic Parameters

Each spectrum produced by the analysis displayed the maximum response for systems with natural periods from zero to four seconds. The natural period of the system was modified by changing the stiffness of the brace, *k*, which was modified by changing its cross-sectional area.

The displacement at which the stiffness increases, $\delta_{y,}$ varied between 12.7 cm (5 inches) and 63.5 cm

(25 inches), where 63.5 cm was close to the average maximum ground displacement of the suite of ground motions. While these displacements seem large for a single story frame, they are not unusual for taller, longer period structures. Because the hyperelastic material is thought to be more effective for longer period structures, examination of larger δ_y was important.

The stiffness ratio, α, was varied between 0.1 and 1.0, which represents the elastic case. The frame was also analyzed with a traditional buckling-restrained steel brace. This allowed comparison of the performance between an elastic system, a traditional system, and various hyperelastic systems.

5.2. Ground Motions

The acceleration time histories used for the parametric study were developed for the SAC Joint Venture steel project (Somerville et al., 1997). These ground motions were selected and scaled to match the design spectrum for Los Angeles with a 10% chance of exceedance in 50 years over a wide range of periods. This made the suite ideal for the parametric study where it was important to see at what periods the behavior of the hyperelastic system outperformed the traditional system. Figure 5 shows the elastic spectra with 2% damping for each ground motion of the suite along with the mean response spectrum.

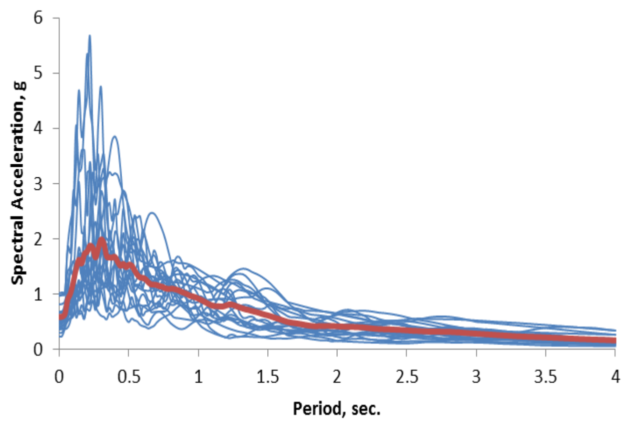

Figure 5. Elastic response spectra of ground motions used in the parametric study (2% damping)

5.3. Results of the Parametric Study

The results of the parametric study give some sense as to where the hyperelastic brace may be considered advantageous. Figure 6 and figure 7 show the average response spectra for the acceleration and displacement at the top of the frame for δ_y equal to 25.4 cm (10 inches), respectively.

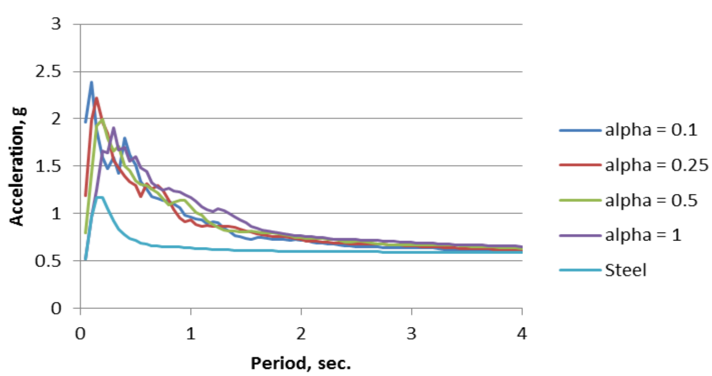

Figure 6. Average acceleration spectra for δ_y = 25.4 cm (10 inches)

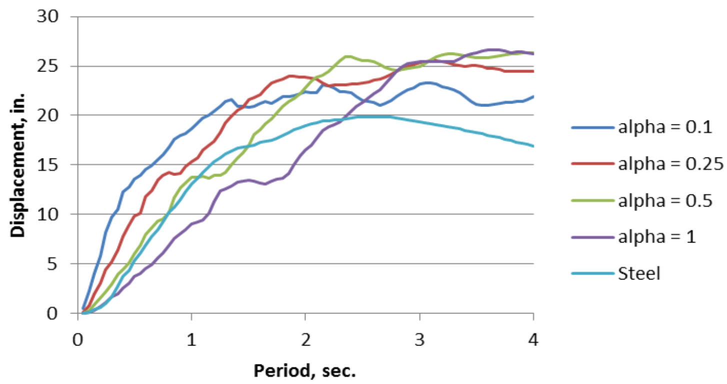

Figure 7. Average displacement spectra for δ_y = 25.4 cm (10 inches)

The figures above show that the traditional system experiences less acceleration than all the other systems and less displacement than the hyperelastic systems over the entire range of periods, but the traditional system did have residual displacements, while the hyperelastic systems did not. The elastic system experienced less displacement for shorter periods, but elastic systems are not economical to build, especially for short period structures.

As mentioned above, the hyperelastic dampers are anticipated to be more beneficial to long-period structures with larger relative displacements. Therefore, the case of δ_y equal to 25 inches is pertinent to the investigation. Figure 8 and figure 9 show the average response spectra for this case.

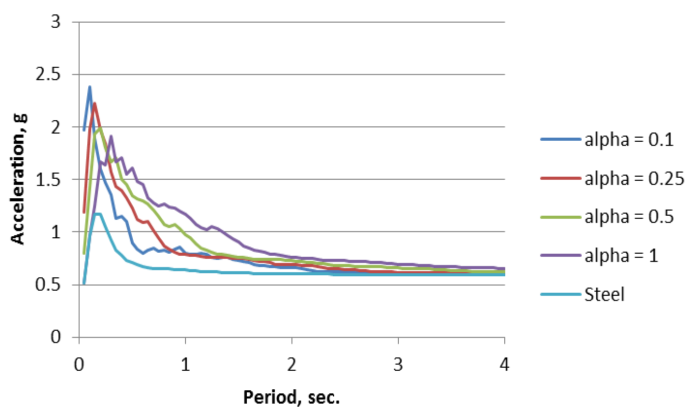

Figure 8. Average acceleration spectra for δ_y = 63.5 cm (25 inches)

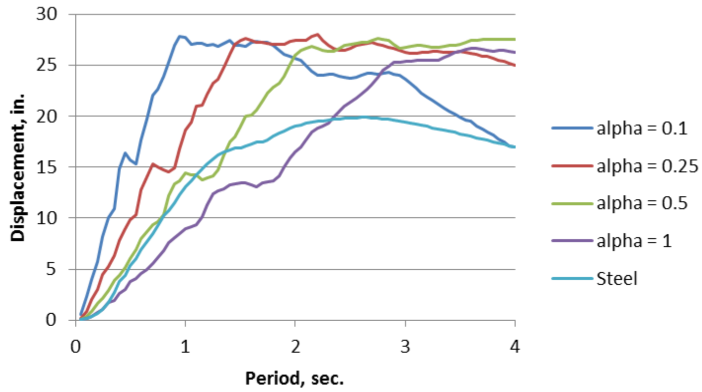

Figure 9. Average displacement spectra for δ_y = 63.5 cm (25 inches)

The above figures show that for natural periods greater than three seconds, the acceleration experienced by the different systems is nearly identical. For periods approaching four seconds, the displacement experienced by the hyperelastic system with α equal to 0.1 approaches that of the traditional system. Therefore, for a period of four seconds, the response of a hyperelastic system and a traditional system is nearly the same. However, the traditional system still had residual displacements and the hyperelastic systems did not.

6. CONCLUSIONS

The results of the parametric study are significant because the hysteretic behavior of the steel brace is such that there will be large amounts of residual displacements after a seismic event, while the hyperelastic damper is designed to eliminate such permanent deformations. Even if a structure endures an earthquake without collapse, the residual displacements may make restoration of the structure cost-prohibitive. Therefore, the benefit of eliminating residual displacements could outweigh the higher cost of the hyperelastic damper even if the response during the earthquake is similar.

In order to fully understand the possible benefits of hyperelastic systems, we recommend that a more expansive study involving multiple-degree-of-freedom systems be investigated. The results of that investigation along would determine if an experimental study is warranted.

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