

Response analysis of hybrid damping device with self-centring

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ABSTRACT: Lead extrusion dampers have been used to dissipate seismic energy in structures and can contribute to damage avoidance design (DAD) rocking connections. In rocking connections that utilises unbound post-tensioned tendons, re-centering of the overall structure is typical. However, the lead extrusion dampers alone are strictly dissipative, have no inherent self-centering and without careful integration into a structural system can lead to residual story drifts. In this study a modified version of High Force-To Volume (HF2V) extrusion damper is introduced to overcome the lack of inherent re-centring, while maintaining the energy absorption capability. The new device is a combination of HF2V and ring spring dampers to provide an overall device with large energy dissipation and inherent self-centering. Response spectral analysis for multiple, probabilistically scaled earthquake suites are used to delineate the displacement reduction factors due to the added damping. Hysteresis analysis of the device under a variety of seismic loadings are also performed and design plots are provided for different sized dampers. Overall, the results indicate an important trade-off between force contributions from the HF2V and ring spring components. Moreover, increasing the ring spring participation force level leads to less residual displacement in exchange for less reduction in peak displacement. This approach of larger ring spring contributions shows less dependence on the structural period, indicating a robustness of the design to a broad spectrum of ground motion inputs.

1 INTRODUCTION

Damping plays an important role in structural dynamics and despite being an active area of research for a long time is one of the least understood topics. Different structural dampers are used to mitigate vibrations and improve structural damping capacity. The aim of this research is to introduce a supplementary damping device that generates energy dissipation and contributes to a damage avoidance designs (DAD) rocking structural system.

Lead extrusion dampers were designed to dissipate earthquake response energy in a damage-free manner (Robinson and Greenbank 1976). A new generation of lead extrusion dampers were introduced by Rodgers (2009) which were much smaller than those in Robinson and Greenbank (1976). These high force to-volume (HF2V) energy absorbers are low-cost to manufacture which makes them a suitable device to use within a structural connection. However, the lack of inherent self-centering force could increase the residual displacements of retrofitted structures with respect to those obtained from the as-designed rigid jointed frame.

Ring springs are reliable, totally passive dampers that will be incorporated into hybrid damping devices with HF2V dampers and provide inherent self-centering force as well as energy dissipation under seismic loading. Ring springs show no degradation during subsequent loading cycles (Shepherd & Erasmus, 1988). The implementation of Ring springs in low damage designs have been studied in the past. Khoo, Clifton and Butterworth (2012) employed ring springs to provide a recentering mechanism for Sliding Hinge Joints (SHJ). Also Tait, Finnegan and Sidwell (2013) utilised ring springs at the base of the columns of a rocking frame structure since built in wellington, to set the performance criteria at which the onset of rocking occurs and to reduce impact loads. Since ring springs are velocity independent devices, their performance is not influenced by rate of loadings.

However, if hybrid damping devices are developed that couple ring springs with velocity dependant damping, such as HF2V or traditional fluid viscous dampers, velocity effects become a much more important consideration. This study aims to investigate the velocity dependence of the hybrid device, study the force participation of each component in both quasi-static and dynamic loading cases, and provide a design methodology which relates the static design to the full dynamic behaviour.

1.1 Transient model of the HF2V component

Consider a damping system of the Maxwell type which is schematically presented in Figure 1. The displacement across the spring and the damper are defined by x and y respectively and z , the total displacement of the system is a known input time varying displacement function. Therefore:

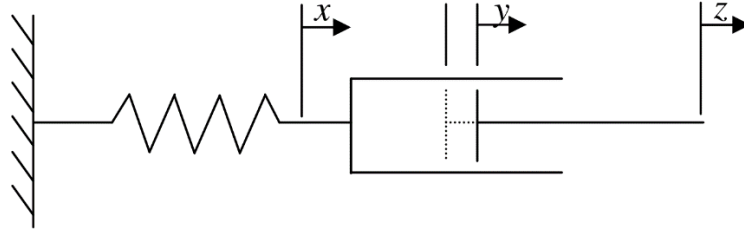


Figure 1. Schematic diagram of the HF2V component.

$$\begin{aligned} x + y &= z \\ \dot{x} + \dot{y} &= \dot{z} \end{aligned} \quad (1.1)$$

Using the Pekcan, Mander, & Chen, (1999) model for non-linear viscous damping and considering the fact that the spring force and the damper force are equal to the applied force:

$$F_D = \text{sgn}(\dot{y})C_\alpha |\dot{y}|^\alpha = x / f_D \quad (1.2)$$

where C_α is the damper coefficient, F_D the force within both the spring, \dot{x} the velocity across the spring, \dot{y} the damper velocity and damper and f_D the axial flexibility of components of the damper assembly. α is the velocity exponent and $\alpha \leq 0.11$ for HF2V devices. sgn is the sign function.

$$\dot{x} = f_D \dot{F}_D \quad (1.3)$$

Substituting Equation (1.1) into Equation (1.3) yields:

$$\dot{y} = \dot{z} - f_D \dot{F}_D \quad (1.4)$$

and substituting Equation (1.4) into Equation (1.2) yields:

$$\left(\frac{F_D}{C_\alpha} \right)^{1/\alpha} = \dot{z} - f_D \dot{F}_D \quad (1.5)$$

Finite difference discretization for \dot{z} and \dot{F} :

$$\Delta t \left(\frac{F_D}{C_\alpha} \right)^{1/\alpha} + f_D F_{D,i+1} = z_{i+1} - z_i + f_D F_{D,i} \quad (1.6)$$

The following relationship can be obtained:

$$F_{D,i+1} = C_\alpha \left| \frac{z_{i+1} - z_i + f_D F_{D,i}}{\Delta t + f_D C_\alpha^{1/\alpha} F_{D,i+1}^{1-1/\alpha}} \right| \text{sgn} \left(\frac{z_{i+1} - z_i + f_D F_{D,i}}{\Delta t + f_D C_\alpha^{1/\alpha} F_{D,i+1}^{1-1/\alpha}} \right) \quad (1.7)$$

The bracketed expression in Equation (1.7) is \dot{y} at the latest time step, therefore

Equation (1.7) can be written in two equations, defined:

$$\dot{y} = \left| \frac{z_{i+1} - z_i + f_D F_{D,i}}{\Delta t + f_D C_\alpha^{1/\alpha} F_{D,i+1}^{1-1/\alpha}} \right| \quad (1.8)$$

$$F_{D,i+1} = C_\alpha |\dot{y}_{i+1}|^\alpha \operatorname{sgn}(\dot{y}_{i+1})$$

The coupling of predictor corrector Equations of (1.8) accurately models the HF2V component behaviour by using appropriately small time steps and/or addition of iterations as discussed in Rodgers, (2009).

1.2 Ring spring energy dissipator

Ring spring components add self-centering mechanism to the hybrid device and consists of a series of separate inner and outer ring elements with mating taper faces assembled in columnar form (Figure 2). Sliding action of mating elements provides energy dissipation due to the friction between the inner and the outer ring elements. The application of axial load results in circumferential tension for the outer rings and compression for the inner rings. Independent characteristic of loading rate, simple and compact design, independent of temperature and being totally passive make ring springs a suitable choice to combine with an HF2V device to create a hybrid damping device.

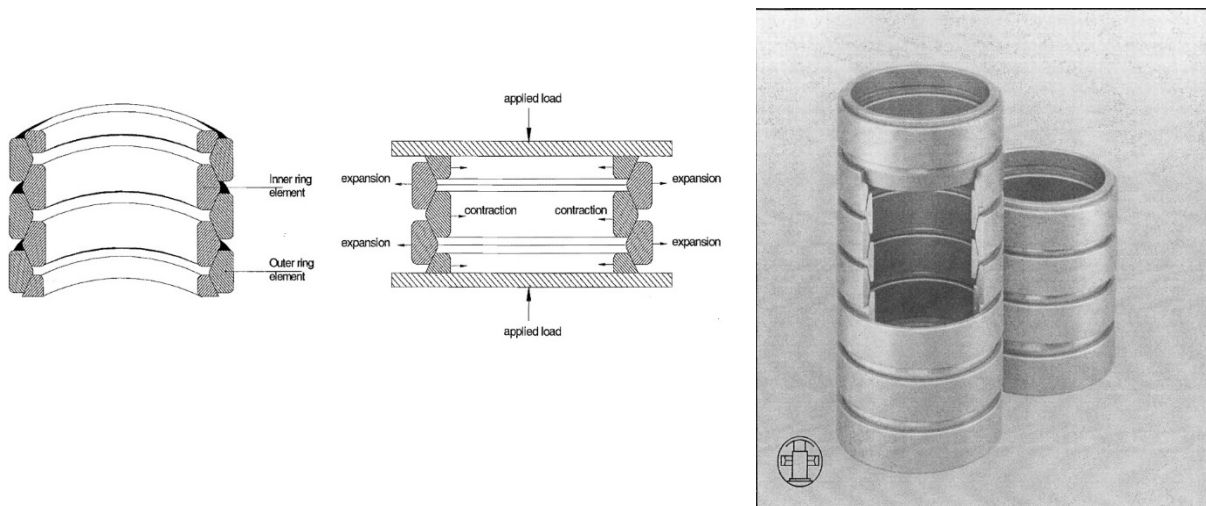


Figure 2. Schematic diagram of the ring spring components (Bishay-girges 2004).

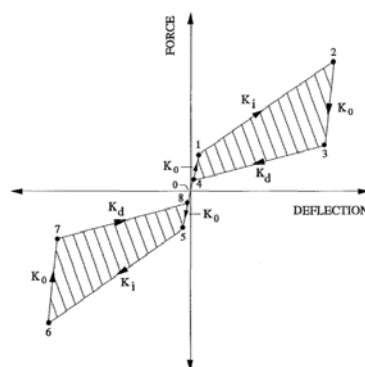


Figure 3. Force deflection diagram for pre-loaded ring springs (Hill 1995).

The ring spring stiffness characteristics are shown in Figure 3 where K_0 is the elastic stiffness, K_i stiffness during loading and K_d stiffness during unloading.

1.3 Hybrid device

The non-linearity of the hybrid device and the unpredictable nature of the ground motions spectrum make it difficult to predict the exact force participation of each components of the device under seismic loadings. Since these devices are designed based on quasi static loading, their behaviour under dynamic loadings could be different. The ring spring behaviour is independent of velocity, while the HF2V device have a weak velocity dependence. Therefore a thorough analysis is needed to investigate the possible scenarios under different ground motions. The design force for the hybrid device is set to be 10% of the structural weight. Each component's force participation corresponds to a fraction of the overall design force, which is expressed as a percentage of seismic weight.

$$F = \varepsilon Kx_{ref} + (1 - \varepsilon)C\dot{x}_{ref}^\alpha \quad (1.9)$$

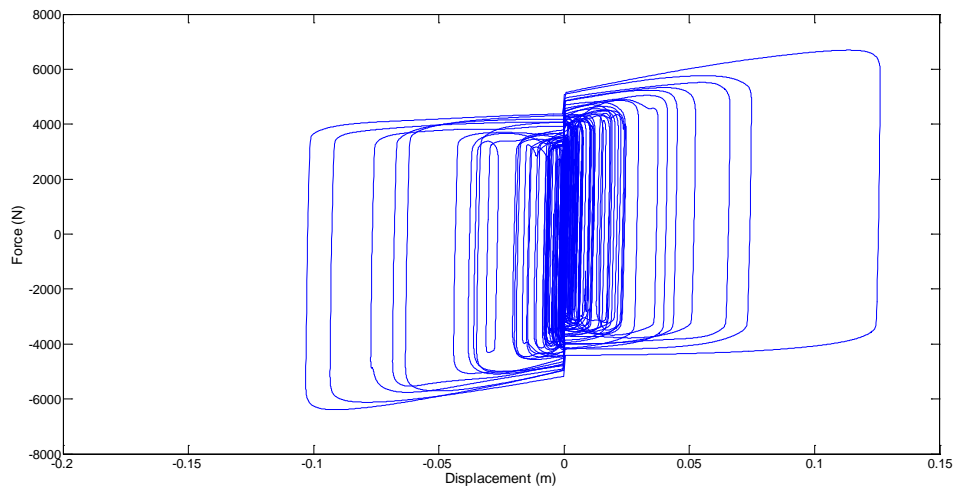
Where ε represents the percentage of force participation of the ring spring component.

2 DEVICE DESIGN AND ANALYSIS

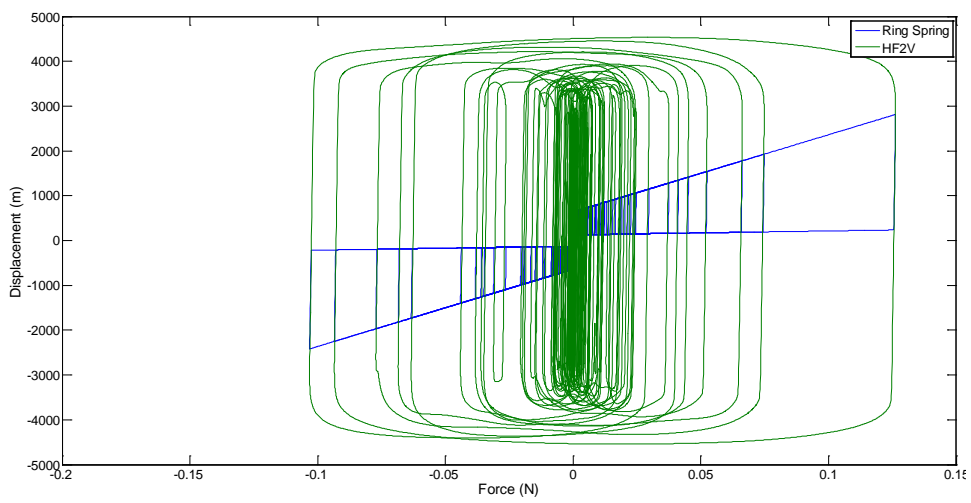
Hysteresis performance of the components of the hybrid device with $\varepsilon = 0.5$ (50% combination from each device) and natural period of 1s subjected to realistic ground motion is shown in the Figure 4. HF2V provides energy dissipation and resisting force dependent upon the structural velocity. Therefore the HF2V device can produce large forces, even in small displacement cycles if the velocity is large. Conversely the ring spring component absorbs energy due to the loading and unloading caused by structural displacement. The resisting force of the component becomes greater for higher structural displacements and is independent of velocity.

The compound device should be able to behave safely under a variety of ground motions. Response simulation of the device is performed under seismic loadings from low, medium and high ground motion suites having probability of exceedance of 50% in 50 years, 10% in 50 years, and 2% in 50 years respectively. Earthquake records are obtained from the SAC project (SAC, 1999; Somerville, 1997) and each suites contains 20 records, giving a total of 60 ground motion recordings.

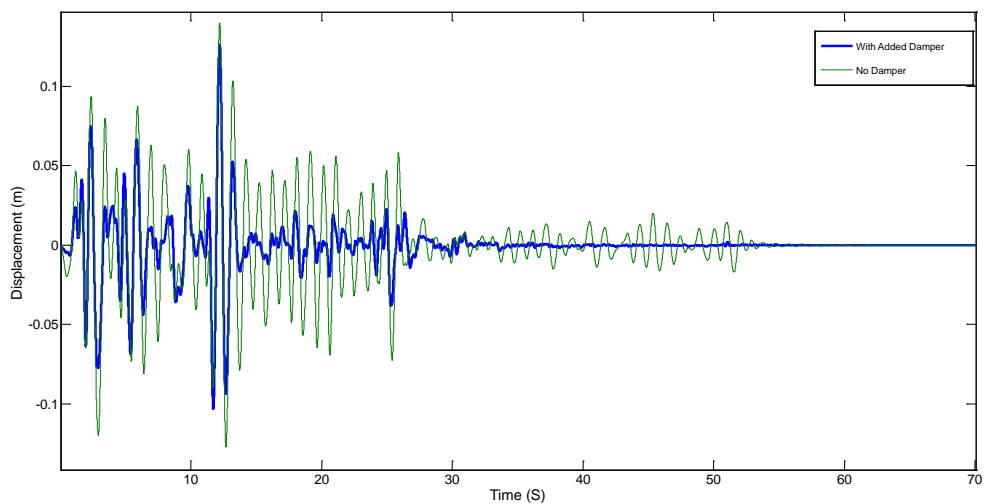
Analysis of the structural response spectra is undertaken for a range of ε from 0% (all ring spring) to 100% (all HF2V device). At structural periods of $T = 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0$ and 5.0 s the spectral response of the system subjected to all 60 ground motions are simulated for each device and the maximum displacement and residual displacements are recorded. Also the maximum output force of each component is reported for each device so one can compare the design (quasi static) and dynamic force participation of each component as shown in Figure 5a. Each participation factor has 480 data points (8 period values and 60 ground motions), represented as individual markers. The solid lines indicate a particular percentile of the results as given in the legend. Period dependence of the device is investigated in Figure 5b where each line represents the median device force participation relation for a specific period. The natural period of the structure does not affect the dynamic force response of the hybrid damper and this indicates that the force envelope in Figure 5a corresponds to the different loading patterns of the earthquake ground motions rather than structural properties.



(a)



(b)



(c)

Figure 4. Hysteresis response of the hybrid damper under Imperial Valley (la01) ground motion a) Hysteresis response of the hybrid device b) hysteresis response of each components c) earthquake displacement profile of the structure with and without added damping.

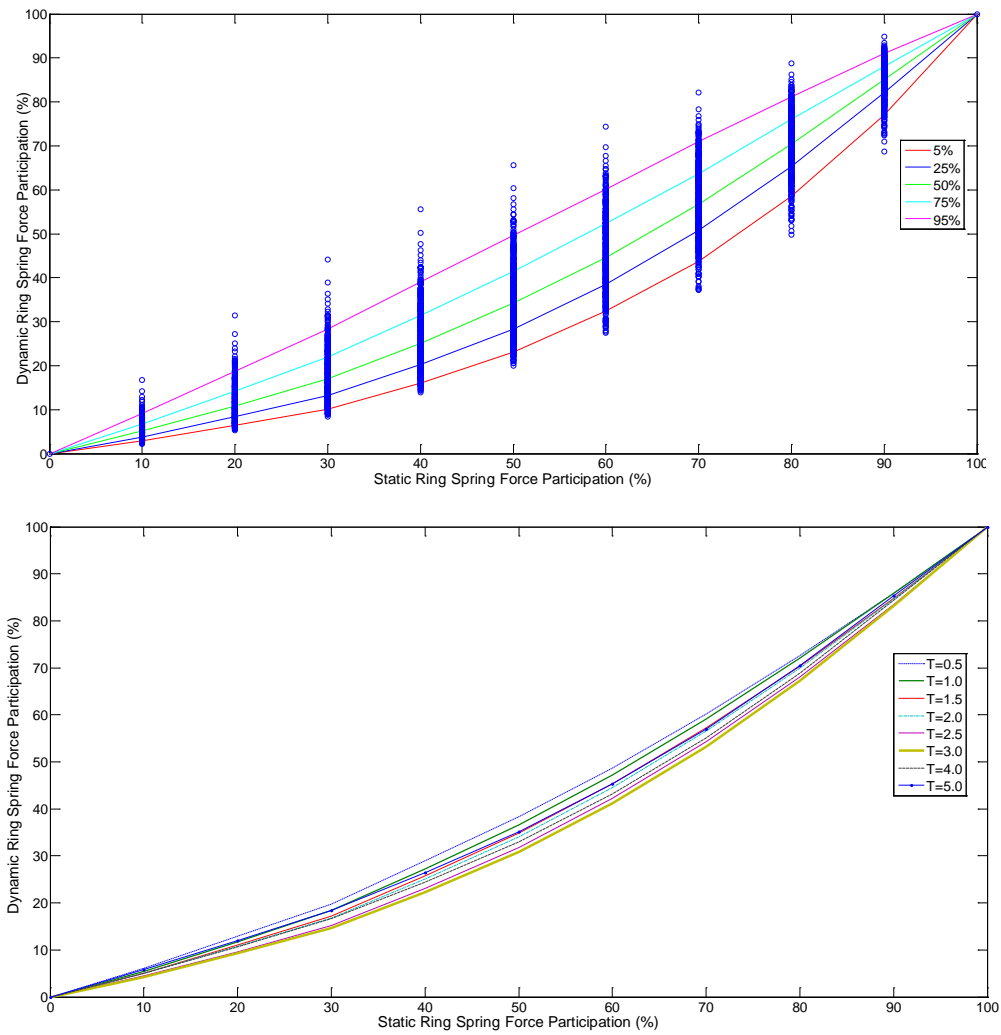


Figure 5. Device's component sizing a) Force participation envelope b) Device's component force participation by period.

The reduction achieved across each suite by addition of the hybrid device is shown in Figure 6 which indicates the robustness in performance of the hybrid damper. Larger ring spring contribution brings more self-centering capability at the expense of less reduction in displacement.

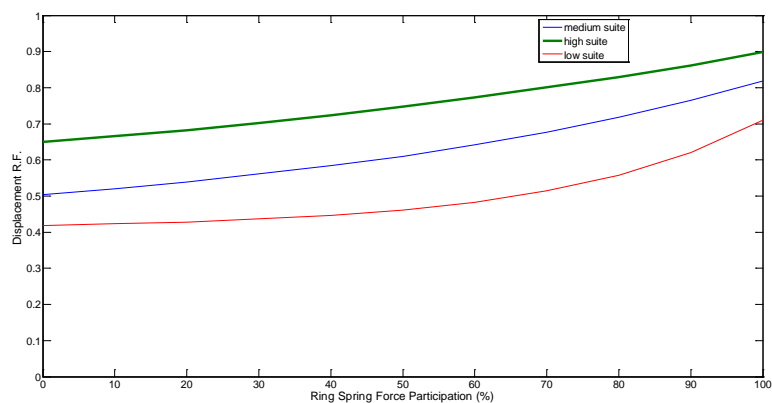


Figure 6. Geometric mean displacement reduction factors for each suite.

Dispersion coefficient of displacement reduction factors for each period are calculated and presented in Figure 7. The dispersion coefficient D , is defined as $D = \frac{\sigma^2}{\mu}$ where σ^2 is the variance and μ is the mean of the maximum displacement reduction factors for each period. The devices which are designed for lower natural structural period tend to respond more consistently under different earthquake ground motions across the different force participation ratios.

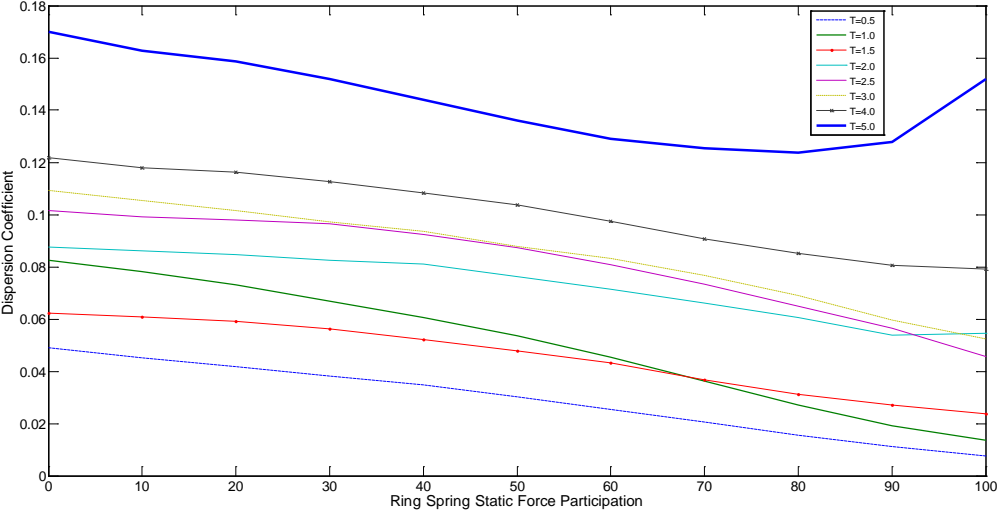


Figure 7. Dispersion coefficient of displacement reduction factors by period.

2.1 Residual Displacement

The maximum residual displacement of the augmented structures are normalized and recorded for each simulation and presented in Figure 8. The normalised values are obtained by dividing the residual drift of the augmented structure by the maximum displacement.

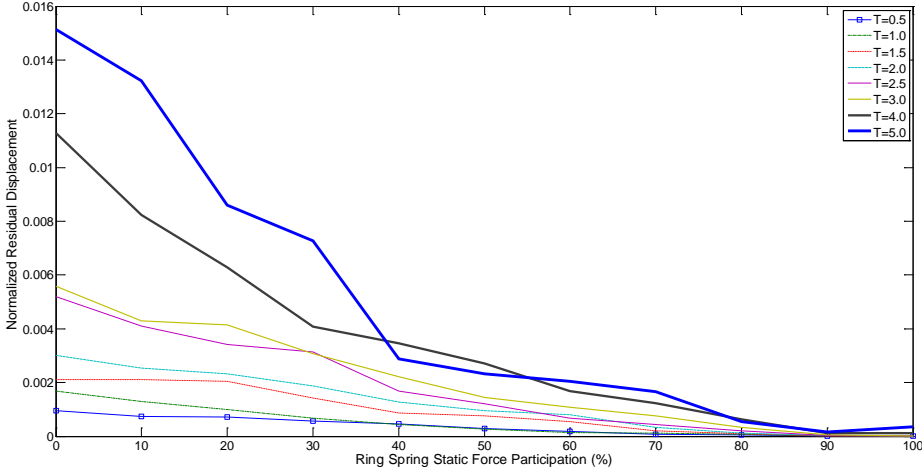


Figure 8. Normalised maximum residual displacement for each structural period.

Structures with only HF2V devices exhibit larger normalised residual displacement, especially for structures with longer natural period where overall displacements are larger and residual displacements are observed. Combining HF2V and ring spring ensures self-centering the energy dissipator without the need for post-tensioning or any other external mechanism to provide overall structure self-centering. It should be noted that none of the structures modelled exhibited excessive residual displacement.

3 CONCLUSION

The concept of a hybrid energy dissipator is introduced. Comprehensive simulation response of structures with a wide range of natural period is undertaken across a range of earthquake suites so the influence of the seismic loading pattern and structural stiffness on the device response are characterized. The analysis of the response spectra shows a significant reduction in the maximum and residual displacement. The reduction factors show the device performs better across low suite ground motions. Dampers with small ring spring force participation (less than 50%) do not perform effectively in reducing the residual displacement especially for higher structural periods (bigger than $T=3$ s). However, even in cases where residual displacements are seen they are not excessive.

While the hybrid device analysis shows significant promise, the static design method used in the research needs to be replaced by a more robust method. Simple design based on a normalised design force does not accurately capture the full velocity dependence and dynamic force contribution. Installing the damper impacts the natural period of the structure and also one device can provide different force capacity based on the loading pattern. These areas are of particular interest for future work.

4 ACKNOWLEDGEMENT

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