16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 1218
Registration Code: S-XXXXXXXX

Impact of Hybrid Damping Devices on Structural Response Parameters, Including Base Shear and Peak and Residual Drifts

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Abstract

The frictional Ring Spring (RS) is a dissipative spring that is used to provide restoring forces and dissipation in a single device. It thus offers significant re-centring capability when used in structural connections to reduce earthquake induced vibrations and maintain/add to its repositioning ability. Working on the basis of sliding contact between double-taper metal rings, a ring spring offers different loading and unloading stiffness's, which provides the energy dissipation of the device and gives the structure a measure of re-centring restoring force.

This research investigates the effects of augmenting a structure with a hybrid dissipation system using ring springs in conjunction with high force to volume (HF2V) dissipaters. The HF2V damper possesses a high level of damping which boosts the dissipative characteristics of the system while using the RS for re-centring. A nonlinear, single degree of freedom system is used to model the behaviour of a building including nonlinear structural stiffness and yielding, as well as nonlinear device models. A spectral analysis is run using a set of 20 different earthquake records and mean response results are presented as reduction factor spectra over a structural period range of 0.2-5.0 seconds in 0.1 second increments, for output parameters comprising: drift, residual displacement, and base shear. These spectral analyses are examined over a parametrised range of RS and HF2V device stiffness and capacities, to determine the trade-offs in the balance between dissipation and restoring force using such a hybrid system.

The results for the best RS and HF2V combination show promising reductions in peak lateral drifts and minimised residual displacements. Compared to the uncontrolled structure, peak drifts and residual drifts are reduced up to 50% and 80%, respectively. However, these reductions are accompanied by an increase in the base shear values for structural periods above 1.0 seconds. These increases range from 10-100% as the period increases to 5.0 seconds. These reduction factor response spectra presented in the results provide mean probabilities of exceedance over a probabilistically scaled suite and could thus be used in a performance based design framework as a guide to select the proper configuration of hybrid damper device.

Keywords: nonlinear structure, spectral design, self-centring, high force damper

1. Introduction

Structural and non-structural components within a building are prone to substantial damage during an earthquake, when significant amounts of energy are transferred to the building within a short time span. To minimize such damage and related economic losses, current design codes are mainly focused on developing sacrificial designs to dissipate energy and ensure life safety. However, the resulting damage can necessitate long interruptions to serviceability and repair, and even total demolition of a building following a major earthquake, resulting in significant economic losses. Hence, there is an increasing demand for structural resilience through damage resistant structural designs that dissipate energy without sacrificial damage to create more resistant next-generation structures.

Intended to curb the economic and business costs of the earthquake via low damage structures, a relatively novel design methodology known as Damage Avoidance Design (DAD) has gained acceptance in the recent years. To realize DAD structures, the energy dissipation mechanism utilized in the structures must essentially show consistence and repeatability in their behaviour over the life time of the structure thus minimising post-quake repairs and disruptions. Thus, repeatable, non-sacrificial energy dissipation is a key element to DAD structures.

High-Force-To-Volume (HF2V) ratio dampers are lead extrusion dampers designed by Rodgers *et al.*, (2007). The device consists of a steel cylindrical container filled with lead and a moving bulged shaft passing through its axis as shown in Fig. 1. It is the successor to an earlier design proposed by Robinson and Greenbank, (1976) as a repeatable way of absorbing energy. Low in cost and easy to manufacture, HF2V devices are a favourable choice to be used in the design of structures. However, the absence of a re-centring mechanism within this device can potentially result in residual deformations throughout the structure.

Ring springs are fully passive frictional dampers with high re-centring capability (Erasmus, 1988; Hill, 1995). A ring spring consists of a stack of inner and outer rings with tapered mating surfaces. When axially compressed, inner rings compress radially, while sliding against outer rings and forcing them to expand radially. This mechanism provides an extremely large stiffness in a relatively small size compared to other types of springs (Hill, 1995). Upon unloading, the rings tend to return to their initial position giving it a re-centring capability. Ring springs have different loading and unloading stiffness values, which gives them a considerable measure of hysteretic damping. This dissipative behaviour, together with its re-centring capability, makes it a favourable candidate for industrial applications where moderate, compact, and reliable energy absorption is needed (Kar *et al.*, 1996; Filiatrault *et al.*, 2000).

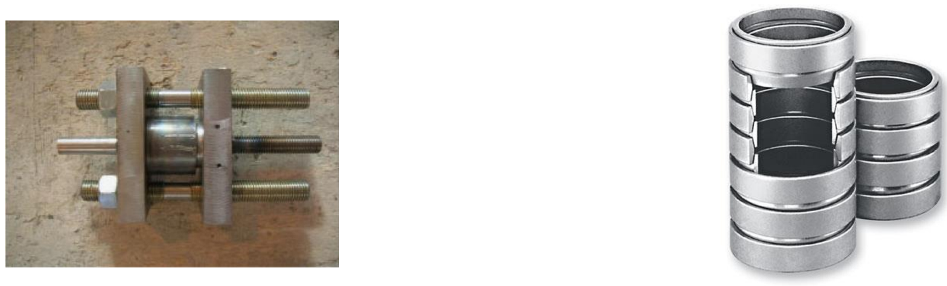

Fig. 1. Prototype lead extrusion damper (Rodgers et al., 2008) (left) and prototype friction ring spring (Hill, 1995) (right)

Minimizing possible damage and/or repair costs is a common goal of structural design. To this end, determining key response metrics of a structure is of utmost importance. This research investigates the effects of using a supplemental hybrid HF2V plus ring spring damping device on the response parameters (displacement, residual displacement, and base shear) of a structure with nonlinear elasto-plastic behaviour. Peak displacement is directly related to the structural damage associated with the deformation of structural components: Residual displacements are associated with the repair cost and damage. Finally, base shear determines the foundation demands. Nonlinear spectral analysis is done for a parametrised set of HF2V and ring spring devices to investigate the best weighting of their contributions to an overall hybrid device.

2. Modelling

A typical simplified SDOF model for spectral analysis is shown in Fig. 2. The system includes a nonlinear elasto-plastic hysteresis loop for the structure equipped with supplemental (HF2V + ring spring) damping. It is subjected to horizontal unidirectional seismic acceleration, $\ddot{x}_g$ as a base excitation input.

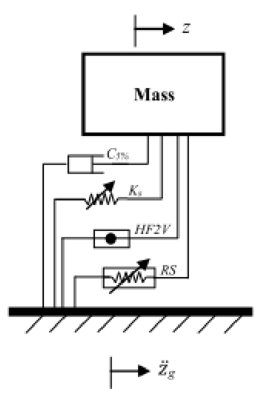

Fig. 2. Schematic configuration of a SDOF system and ground motion input

a) uncontrolled; **b)** controlled (with supplemental devices)

The governing equation for the system shown in Eq. **Error! Reference source not found.**) is defined:

$$m_e \ddot{x} + c\dot{x} + F_{NL} + F_{RS} + F_{HF2V} = -m_e \ddot{x}_g \qquad (1)$$

where m_e is the seismic mass of the structure, F_{NL} is the nonlinear structural restoring force, F_{RS} is the ring spring force, and F_{HF2V} is the lead-extrusion damper force. Nonlinear elasto-plastic restoring force is modelled using the Menegotto-Pinto model (Giuffrè and Pinto, 1970; Menegotto and Pinto, 1973):

$$F_{NL} = \alpha kz + \frac{(1-\alpha)kz}{\left[1 + \left|kz/F_Y\right|^{\beta}\right]^{1/\beta}} \qquad (2)$$

where F_Y is the yield force, and k is the stiffness. The parameters α and β are used to define the shape of the curve, where α is the ratio of post-yield stiffness to pre-yield stiffness and β determines the shape of the transition curve. The lead-extrusion fore has been experimentally shown to be defined (Robinson and Greenbank, 1976; Rodgers *et al.*, 2008):

$$F_D = C_\alpha \left|\dot{y}\right|^{\alpha} = \frac{x}{f_D} \qquad (3)$$

where y is the nonlinear bulge displacement within the cylinder, α is the velocity exponent, C_α is the geometry dependent damper constant, and f_D is the spring flexibility. The bulge moves in series with the elastic shaft (x) giving the device a total displacement of z:

$$x + y = z \qquad (4)$$

Combining Equations (3), (4) and using a time-incremented finite difference method, following relations are derived to evaluate the HF2V force (Rodgers *et al.*, 2008):

$$\dot{y}_{i+1} = \frac{z_{i+1} - z_i + f_D F_{D,i}}{\Delta t + C_\alpha f_D F_{D,i+1}^{\;1-1/\alpha}} \qquad (5)$$

$$F_{D,i+1} = C_\alpha \left|\dot{y}_{i+1}\right|^{\alpha} \times sign\left(\dot{y}_{i+1}\right) \qquad (6)$$

The nonlinear ring spring force depends solely on the direction of motion. Whether it is being stretched (decreasing axial load) or compressed (increasing axial load) the ring spring stiffness will be different:

$$F_{RS} = \begin{cases} K_i x & : Loading \\ K_d x & : Unloading \end{cases} \tag{7}$$

The response of an HF2V device to a sinusoidal input motion is shown in Figure 3a and defined by Equations (4)-(6). Figure 3b shows the ring spring response to a sinusoidal input defined by Equation (7).

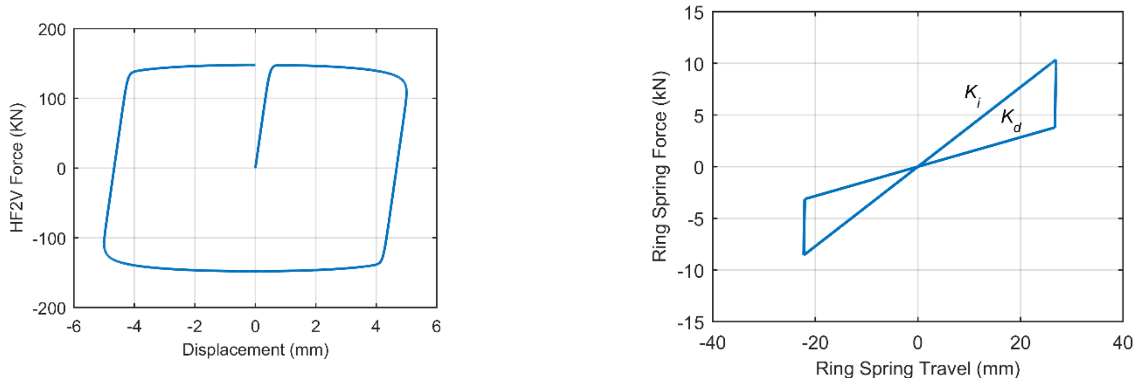

Fig. 3. Schematic configuration (left) and force-displacement behavior of a HF2V device (right)

3. Analysis

To investigate the seismic behaviour of a nonlinear structure augmented with hybrid devices, a nonlinear spectral analysis is carried out using the medium suite of earthquakes from the SAC project (Somerville and Venture, 1997). This suite includes 20 design level earthquakes with a probability of exceedance of 10% in 50 years. A model with the nominal height, $H_e=10\ m$, and seismic mass, $m_e=10^4\ Kg$ together with a 5% structural damping is used in the analysis. Moreover, a yield drift value of $\Delta_y=2\%$ together with parameters $\alpha=5\%$ and $\beta=20$ in Eq. (2) are used to model the nonlinear structural stiffness.

Target response metrics (peak/residual displacement and peak base shear) are collected from nonlinear time history response of the structure for all the earthquake records in the suite and then used to calculate a representative mean value. In accordance with the distribution of the results, geometric mean values are used for log-normally distributed peak displacement and peak base shear, whereas exponential mean values are used for exponentially distributed residual displacement. Using $dT=0.1\ (s)$ period increments, the structural natural period range $T_n=[0.2\text{-}5]\ (s)$ is swept to evaluate the pre-yield structural stiffness for the calculations and generate the response spectra.

The effectiveness of the implemented devices are shown using reduction factor plots. A reduction factor is the ratio of a response metric of a device-supplemented structure to that of a device-free structure. Moreover, two different HF2V configurations ($\varepsilon=5\%$ and $\varepsilon=10\%$) together with two different ring spring configurations ($K_i/K_s = 20\%$ and $K_i/K_s = 40\%$) are used to parametrise the response spectra. The percentage numbers for

HF2V show the nominal force capacity of the device with respect to the structural seismic weight and the representative percentages for ring springs show the ratio of loading stiffness to structural stiffness while the ratio of loading stiffness to unloading stiffness is assumed to be 35%.

4. Results and discussion

4.1 Individual earthquake response

To demonstrate the effect of the hybrid damping device modelled in the previous section, on the behaviour of the nonlinear structure, the response of a structure to the first earthquake record in the suite is shown in **Fig. 4**. The structure has a pre-yield natural period *T=1.5 sec* and its response with and without the hybrid damper is plotted for comparison. Fig. 4a shows that the peak and residual displacement of the device-augmented structure are significantly lower than those of the device-free structure. Fig. 4b shows the separate share of constituents of the total resistive force.

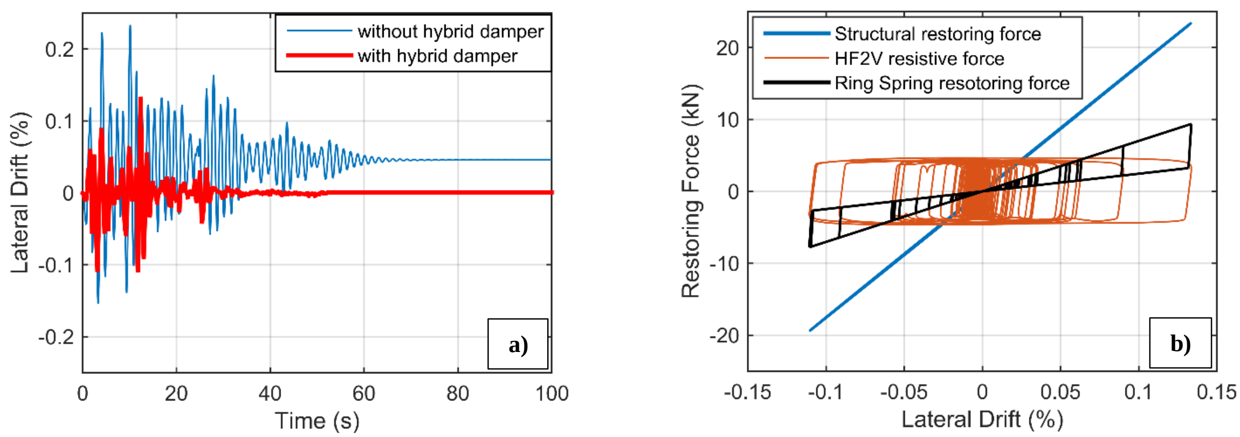

Fig. 4. Response of the structure to an individual earthquake; a) drift response with/without hybrid damper, b) individual force contribution of damping and restoring components

The sum of all restoring and resistive forces imposed by the elastic structure and the added dissipative components (shown in Fig. 4b) are transferred to the structure foundation as a base shear. Fig. 5 shows the total base shear for structures with/without hybrid damping device. The shear-drift plot for the uncontrolled structure is controlled by the hysteretic behaviour of the elasto-plastic structure whereas that of the controlled structure is markedly affected by the contribution from ring spring and HF2V device.

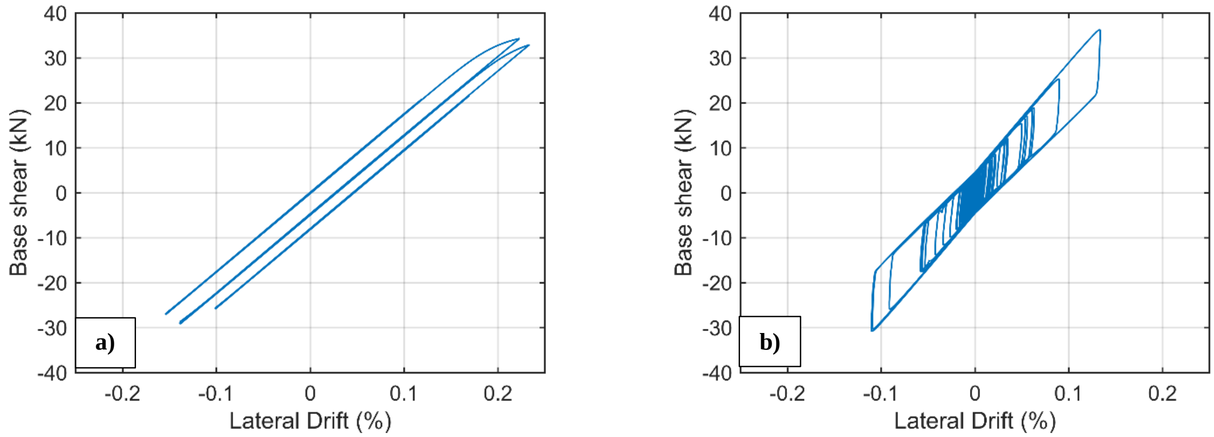

Fig. 5. Base shear response of the structure to the individual earthquake

a) Structure without hybrid damper, b) Structure with hybrid damper

4.2 Displacement reduction factors

The reduction factors (RFs) for displacement response are shown in Fig. 6. The HF2V device significantly decreases the peak displacement results (Fig. 6a) with an average 30% reduction for ε_5 and 45% reduction for ε_{10} whereas only a 10-15% average reduction is seen for RS_{20} and RS_{40} (Fig. 6b). The combination of 5% HF2V and ring springs (RS_{20}, RS_{40}) results in the RFs shown in Fig. 6c. An average value of 0.6 is obtained for the total period range with the difference between RS_{20} and RS_{40} being reasonably insignificant particularly for periods greater than 2 sec. Reduction factors for ε_{10} and two ring springs show a similar trend to those of ε5 (Fig. 6d), but with a further increase in displacement reductions ($RF_{Sd}=0.5$).

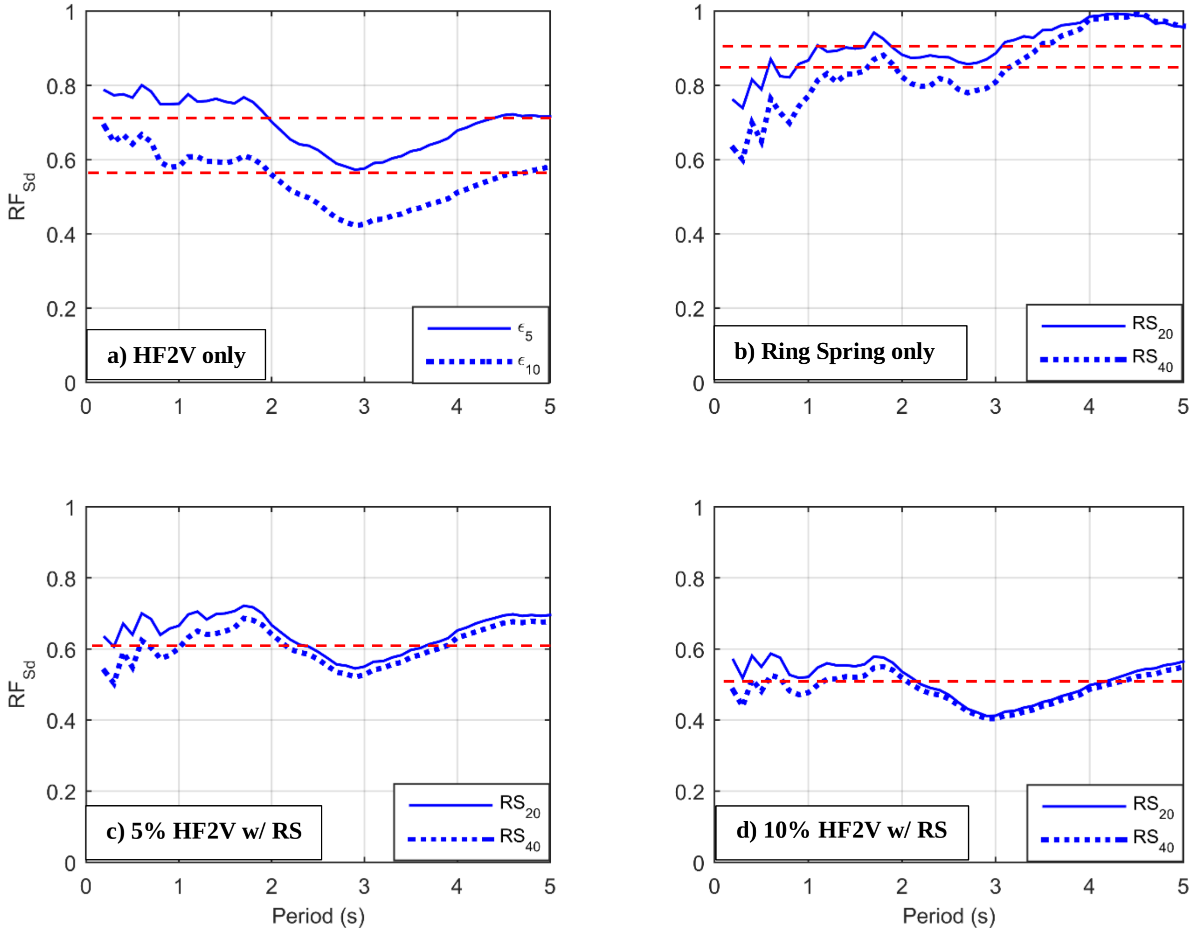

Fig. 6. Displacement RF results for: a) HF2V only; b) Ring Spring only; c) 5% HF2V with both ring springs; and d) 10% HF2V with both ring springs. Horizontal dashed lines show average values for the results across all periods

The relatively small difference between the results of the hybrid device with different ring spring sizes suggests that the use of larger ring springs would not be fully justified based on displacement reductions alone. Overall, HF2V devices provide the primary reductions in peak displacement, where Fig. 6a results are in accordance with the results of Rodgers *et al*., (2008).

4.3 Residual displacement reduction factors

Residual displacement RFs are shown in Fig. 7. Reduced residual displacements with only HF2V (Fig. 7a) are mainly due to the overall decreased displacements throughout the time history. However, the reductions using only a ring spring (Fig. 7b) are associated with re-centring stiffness and the reduced displacement due to the damping from the ring springs. Hybrid devices, show markedly greater average reductions up to 80%, combining the positive effects of HF2V and ring spring (Fig. 7c, d). Hence if the residual displacement is important, then a larger ring spring is more favourable as it provides greater re-centring capability in accordance with expectations.

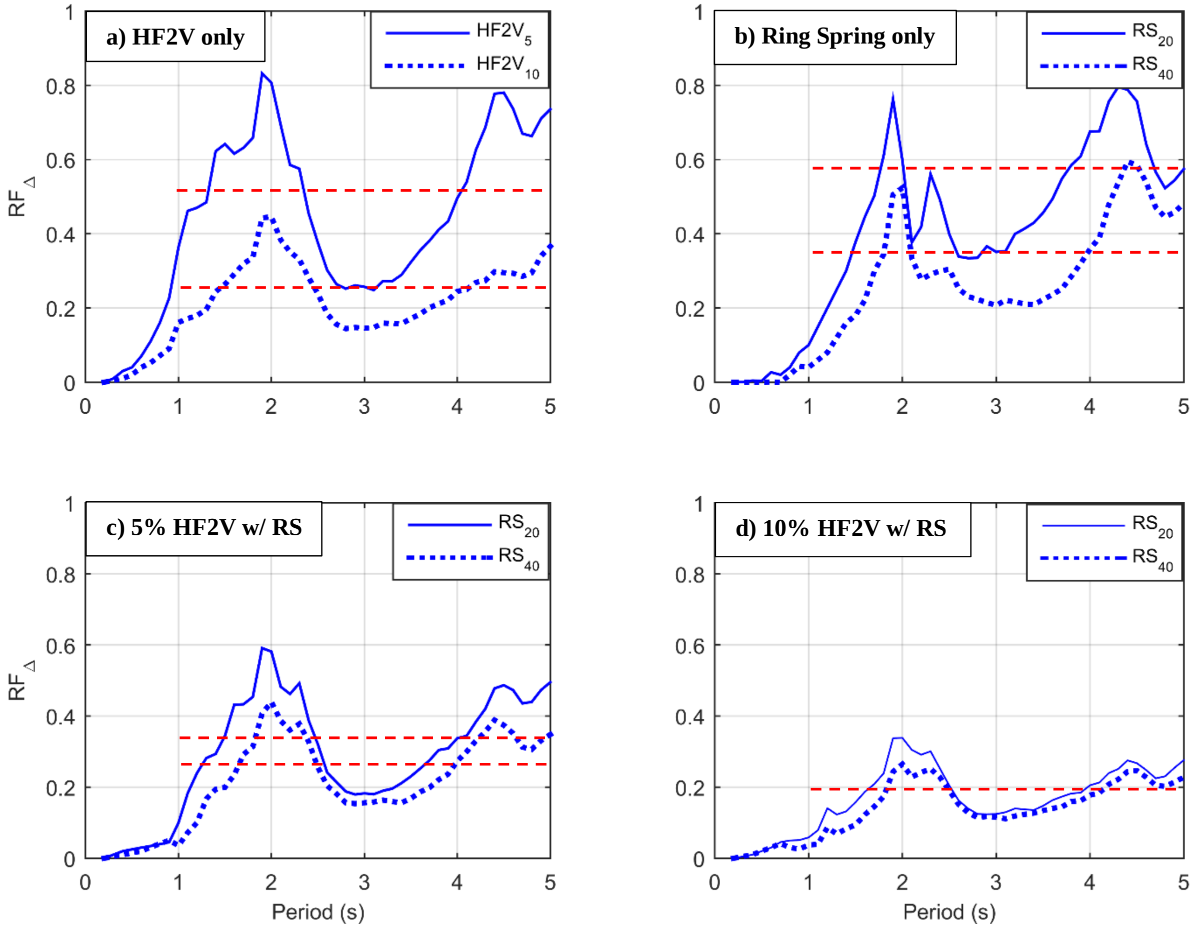

Fig. 7. Residual drift RF results for: a) HFV2 only; b) Ring Spring only; c) 5% HF2V with both ring springs; and d) 10% HF2V with both ring springs. Horizontal dashed lines show average values for the results across all periods

4.4 Base shear reduction factors

Base shear RFs are shown in Figure 6, where a reduction in base shear is observed for structures with periods less than approximately *1 sec*. However, for longer period structures, significantly increased base shear is observed, as a consequence of the resistive and restoring forces imposed by the supplemental components. Such an increase suggests that the forces added to reduce displacements outweigh the reduced structural forces due to those displacement reductions.

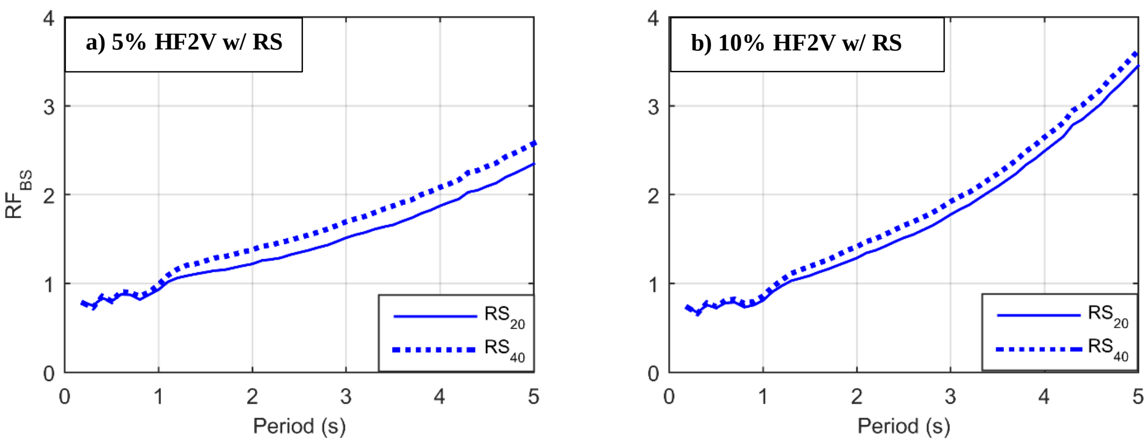

Fig. 8. Base shear RF results for:

a) 5% HF2V with both ring springs; and b) 10% HF2V with both ring springs

5. Conclusions

A non-linear structural response analysis was undertaken to investigate the optimal design of a hybrid damping device. Following conclusive remarks can be made base on this analysis results:

- Using realistically scaled configurations of single dissipaters (HF2V or ring spring) can result in noticeable displacement reductions as a result of their inherent damping capacity.
- Reduction factors for peak transient displacement are almost solely determined by the impact of HF2V devices particularly for larger periods.
- Using a hybrid device results in greater reductions of residual displacements compared to using a single (HF2V or ring spring) device.
- Except for structure with short natural period, supplemental dissipaters result in markedly increased base shear which is dominated by the contribution of HF2V component. Thus, from the base shear point of view, smaller HF2V is preferred for a hybrid device.

These results clearly delineate the necessary contributions from dissipation and re-centring focused devices in creating next-generation DAD structures. The results are presented in a spectral analysis in a form suitable for use in performance based design methods.

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