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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 drift, 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 drifts. Compared to the uncontrolled structure, peak drifts and residual drifts are reduced up to 50% and 70%, 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 0-250% as the period increases to 5.0 seconds. The 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 damping device.

Keywords: *nonlinear structure, spectral design, self-centring, ring-spring, residual drift*

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. It requires the use of dissipaters with proven consistence and repeatability in behaviour. Two of such devices are studied in this research. 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. 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. 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 damper on the structural response parameters (drift, residual drift, and base shear) of a structure with nonlinear elasto-plastic behaviour. Peak drift is directly related to the structural damage associated with the deformation of structural components; Residual drifts are associated with the repair cost and damage. Finally, base shear represents the foundation demands. Nonlinear spectral analysis is done for a parametrised set of HF2V and ring-spring devices to investigate the best weighting of force contributions from these damping components 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 + RS) damping. It is subjected to horizontal unidirectional seismic acceleration, $\ddot{z}_g$ as a base excitation input.

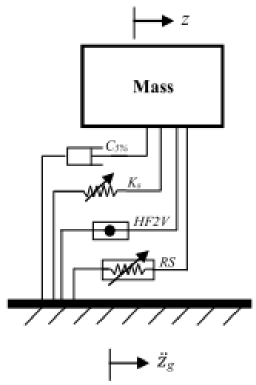

Fig. 2. Schematic configuration of a SDOF system and ground motion input

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

The governing equation for the system shown in Eq. (1) is defined:

$$m_e\ddot{z} + c\dot{z} + F_{NL} + F_{RS} + F_{HF2V} = -m_e\ddot{z}_g \tag{1}$$

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 (Menegotto and Pinto, 1973):

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

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 force has been experimentally shown to be defined (Rodgers *et al.*, 2008):

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

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 (Rodgers *et al.*, 2008):

$$x + y = z \tag{4}$$

An iterative finite difference method is used to solve Eqs. (3), (4) simultaneously (Rodgers *et al.*, 2008). 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 (Hill, 1995):

$$F_{RS} = \begin{cases} K_i z & : Loading \\ K_d z & : Unloading \end{cases} \tag{5}$$

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 drift and peak base shear) are collected from nonlinear time history response of the structure for each earthquake record in the suite and then used to calculate the response ratio of controlled (device-supplemented) response to uncontrolled (device-free) response. This ratio is referred to as the reduction factor. In accordance with the distribution of reduction factors, geometric mean values are used for log-normally distributed peak drift and peak base shear, whereas median values are used for exponentially distributed residual drift to produce representative metrics. Using $dT=0.1\ (s)$ period increments, the structural natural period range $T_n=[0.2\text{-}5]\ (s)$ is swept to generate the reduction factor spectra.

The effectiveness of the implemented devices are shown using reduction factor plots. Moreover, a HF2V device with 5% nominal capacity together with a ring-spring configuration of ($K_d /K_i=35\%$ and $K_i /K_s=40\%$) is used to generate the response spectra. The percentage number for HF2V shows 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 unloading stiffness to loading stiffness and ratio of loading stiffness to structural stiffness.

The values of 5% storey weight for the HF2V device force capacity is defined from prior analyses done on steel beam-column connections (Rodgers *et al.*, 2007) where it gives achievable device forces offering significant reductions in the displacement response. Similarly, the 40% stiffness ratio used for the ring-spring is selected from a range of practical stiffnesses that offer considerable re-centring capability as this was the primary reason for their use (Khoo *et al.*, 2012).

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. 3. 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. 3a shows that the peak and residual drift of the device-augmented structure are significantly lower than those of the device-free structure. Fig. 3b shows the separate share of constituents of the total resistive force.

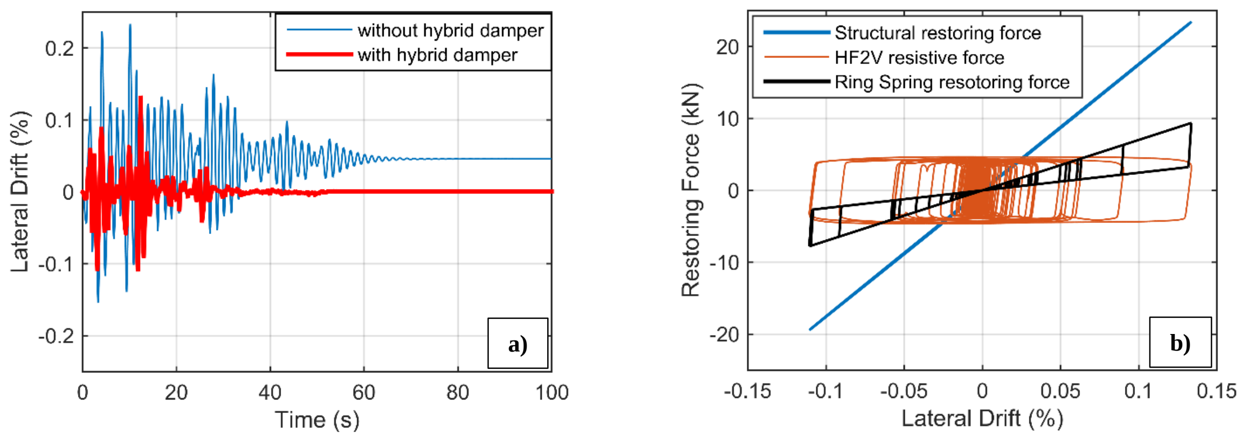

Fig. 3. Response of the structure to an individual earthquake; a) drift response with/without hybrid damper, b) individual force contribution of damping and restoring components

4.2 Drift reduction factors

The reduction factors (RFs) for drift response are shown in Fig. 4. The HF2V device significantly decreases the peak drift results with an average 30% reduction whereas only a 15% average reduction is seen for the ring-spring. The combination of 5% HF2V and 40% ring-spring (RS_{20}) results in the RFs with an average value of 0.6 for the total period range. This reduction shows the benefit of using a hybrid device over the use of a single dissipater. The trend of the results show that for higher periods, the reduction in drift response is mostly controlled by the effect of HF2V device.

4.3 Residual drift reduction factors

Residual drift RFs are shown in Fig. 5. Reduced residual drifts with only HF2V are mainly due to the overall decreased displacements throughout the individual time histories. However, the reductions using only a ring-spring are associated with re-centring stiffness and the reduced displacements due to the damping from the ring-springs. Hybrid device, shows a greater average reduction of 70%, combining the positive effects of HF2V and ring-spring. The trend in the reduction spectra show the dominating effect of ring-springs. Thus, if the residual drift is important, then a larger ring-spring is more favourable as it provides greater re-centring capability in accordance with expectations.

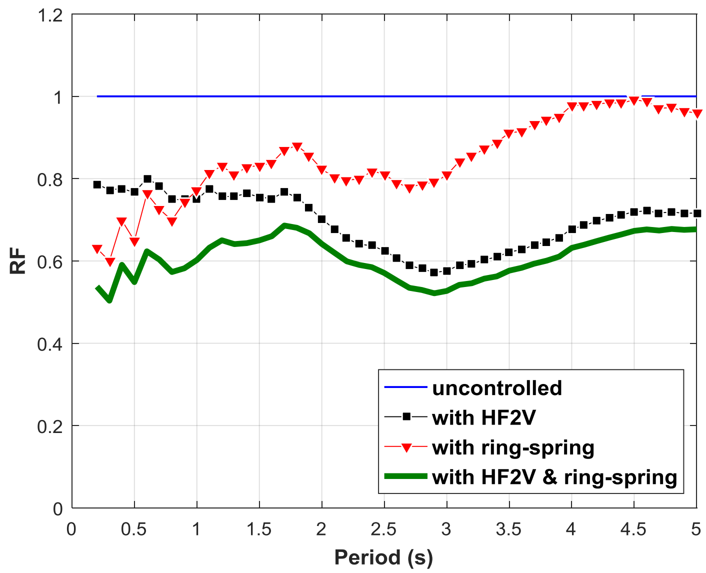

Fig. 4. Drift RF results for: HF2V only; ring-spring only; and HF2V with ring-spring

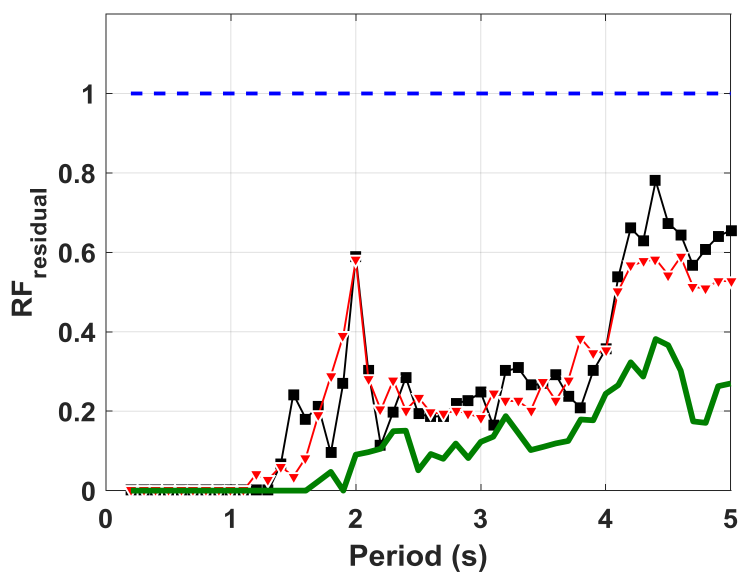

Fig. 5. Residual drift RF results for: HF2V only; Ring-spring only; and HF2V with ring-spring

4.4 Base shear reduction factors

Base shear RFs are shown in Fig. 6, where a reduction (*RF<1*) 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 drifts outweigh the reduced structural forces due to those drift reductions. It should be noted that, while the base shear reduction factors are large at very long periods, the absolute value of base shear forces are quite low, as expected. Therefore, while these results do indicate a notable relative increase in base shear demand from the addition of damping, the absolute level of this demand is relatively low.

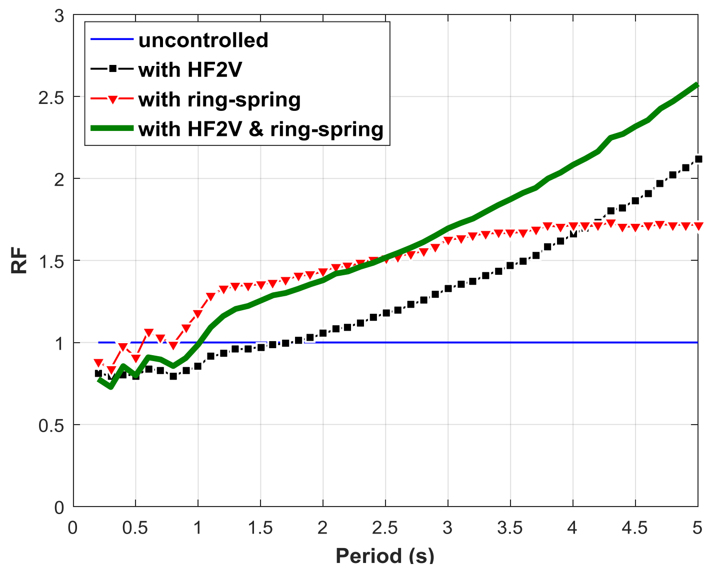

Fig. 6. Base shear RF results for: HF2V only; ring-spring only; and HF2V with ring-spring

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 hybrid damping device (HF2V plus ring-spring) can result in noticeable drift reductions as well as reduced residual drifts due to the combined dissipative effect of HF2V and re-centring capability of ring-spring.
- The use of a hybrid device for a structure with a relatively high period, comes with an increase in the demand on the restoring/resistive force provided by the supplemental damping system. This result requires a trade-off analysis between the reduced drifts and increased base shear, to obtain a suitable overall design balance.

These results clearly delineate the necessary contributions from dissipation and re-centring focused devices in creating low-damage seismic resistant structures. The results are presented in a spectral analysis as a generalizable result. The optimal combination of device force contributions depends upon the specific application and structural design parameters, such as whether an increase in base shear can be tolerated in a given design.

6. Acknowledgements

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