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Design and Experimental Validation of a Re-centring Viscous Dissipater

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ABSTRACT

The design and experimental validation of a passive, hybrid self-centring supplemental damper for low-damage structures is presented. The device combines rate-dependent dissipation of a viscous damper with the rate-independent dissipation and re-centring restoring force of a ring-spring in a parallel fashion. Experimental proof-of-concept validation tests use sinusoidal displacement inputs consisting of [25, 30] mm amplitudes and [0.25–1.75] Hz frequencies, for two levels of ring-spring pre-load equal to 21% and 34% of the design force. Each component is tested individually to characterise and delineate their specific contributions to the overall device. The ring-spring has a design force capacity of 26 kN and a return stiffness ratio of 34% that remain independent of the velocity input. The viscous device input velocities of [50–330] mm/s provide velocity dependent dissipative forces with a maximum of 22 kN at the maximum input velocity. Individual results in summation match the hybrid device results for the same input, indicating no loss of efficiency in the hybrid device load transfer. Overall, these results offer a range of new, easily implemented options for energy dissipation in developing low-damage structures, which can also provide necessary re-centring capability within the same package. The overall method is readily generalised for a wide range of hybrid device force capacities and design requirements.

1. Introduction

Earthquake ground motions can be highly damaging for urban buildings and structures [1,2]. Repair and downtime costs associated with seismic damage and subsequent interrupted building use and access is often substantial. For example, widespread structural and non-structural damage to urban commercial facilities in the 2011 Christchurch, New Zealand earthquake had an estimated total cost of NZ$40 billion [3,4].

Current structural design procedures minimise loss of lives, linked with earthquake damage through the use of sacrificial damage and energy dissipation elements [5]. While increasing life safety, this approach can result in significant post-quake damage [6,7]. Such damage may even result in a building demolition when the damage is infeasible or too costly to repair [8,9]. Ongoing research to implement innovative dissipation techniques in structural mitigation [10,11] indicates a growing appeal for an increased economic resilience through low-damage structures that ensure both life safety and structural serviceability after a major event.

A range of alternative seismic design principles and strategies have been considered including damage avoidance design (DAD). DAD aims to minimise the economic costs of earthquakes by eliminating damage and the subsequent need for significant post-quake repairs, thus reducing downtime and increasing use and serviceability. This design philosophy was first introduced by Mander and Cheng [12] for damage-free design of bridge piers. The overall DAD approach switches energy dissipation from sacrificial damage of structural elements to repeatably used supplemental dissipation mechanisms [13–15].

Rodgers et al. [16] used DAD principles to create highly repeatable low-damage beam-column assemblies using a supplemental high-force-to-volume (HF2V) damper. Semi-active and passive devices have also been proposed for these roles [17,18]. For such structures with supplemental energy dissipation, consistency and repeatability of dissipative behaviour, together with minimum degradation over time, are essential characteristics of the dissipative element. These characteristics meet DAD goals of avoiding the need for substantial maintenance/repair after a strong earthquake motion. Experimental validation of two of such dissipative devices, a rate dependent viscous device, and a rate independent ring-spring is the focus of this research.

Fluid viscous dampers are fully passive dissipation devices that have proven effective in mitigating seismic structural response [19–22]. These devices can be used as supplemental retrofit devices in otherwise conventional structures. They are more viable compared to costly base isolation mechanisms that are usually only incorporated in the initial design of new structures [23]. Moreover, low complexity and quick response makes these viscous fluid devices a favourable supplemental

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dissipation option in earthquake-prone structures [24].

Lack of inherent re-centring capability in viscous devices can result in a permanent offset or residual displacement, which coupled with the inelastic behaviour of the structure can lead to residual deformations throughout the structure [25]. To minimise this undesirable outcome, re-centring forces must be included either by structural design [26] or by using hybrid devices [27,28]. In this research, a dual hybrid supplemental damper consisting of viscous damper and ring-spring is designed to provide dissipation and re-centring restoring force. The hybrid device is experimentally validated in this research.

Ring-springs are friction based energy dissipation devices with self-centring restoring forces [29,30]. A ring-spring essentially consists of a stack of inner and outer rings with tapered mating surfaces. When the stack is axially loaded, the inner rings undergo compression while the outer rings undergo tension. Thus, the rings slide along each other and reduce the overall length of the stack. When the force is removed, the rings slide back to their unloaded position due to the radial forces within them. The friction at the sliding surfaces creates a form of rate-independent and thus set amount of dissipation and the radial forces provide re-centring capability. Ring-springs offer a significant spring force in a compact volume that traditional springs cannot [31,32], making them attractive for structural applications.

This paper presents the design and experimental validation of a hybrid re-centring dissipation device. This combination offers new options for low-damage dissipation and uptake by industry where devices with similar behaviour have been successfully employed [33]. Prior work has used ring-springs in sliding friction connections [34]. However, these friction connections can often suffer damage in use [35,36] and have variable performance based on assembly and steel coating [37]. Coupling with a highly repeatable and rate dependent dissipation offers the opportunity to improve dissipation performance, especially in proportion to input, and to improve repeatability and minimise repair/inspection.

These results provide a necessary research step justifying full-scale testing and eventual structural implementation of the proposed hybrid device. A comprehensive spectral analysis is also necessary to assess the efficacy of the concept across a range of structural periods and design level ground motions. This approach has been used to assess the applicability of other similar low-damage dissipaters where linear/non-linear response spectra predict the effectiveness of such devices in a wide range of uses [38,39].

2. Device design

2.1. Viscous device

The viscous device has a typical configuration consisting of a fluid filled steel housing and a shaft-piston coupling along its axis. The piston is fixed on the shaft and divides the fluid cavity into two parts. Shaft motion forces the damping fluid inside the housing to flow from one side of the piston to the other side through the holes (orifices) on the piston, imposing a resistive force against shaft motion (damping). The size and configuration of the orifices on the piston, as well as the piston area, determine the level of damping provided [40].

The piston in Fig. 1 has a diameter of 101.6 mm (4 in.) and thickness of 20 mm with 6 × 3.5 mm orifices unblocked at 45 mm pitch circle diameter. The shaft is 31.75 mm (1.25 in.) in diameter and maximum device stroke is ± 50 mm. SAE 80W-90 Castrol Axle oil with viscosity of 140 cSt at 40° is used as the damping fluid for the viscous device. Endcaps are sealed using 14 M8 hexagonal cap screws and rubber seal rings around the endcap, and O-rings around the shaft in the endcap to prevent leakage.

2.2. Ring-spring

The ring-spring is shown in Fig. 2. It consists of a ring stack mounted on an inner guide (shaft) and enclosed inside an outer guide (housing). Ringfeder rings, with 19 inner rings and 20 outer rings of type 1205 were selected to form the ring stack [41]. Fig. 2 also shows the basic dimensions of the rings, as well as the mating of outer and inner rings. The guides ensure axial deformation of ring column by preventing non-axial misalignment.

In an unloaded condition, the stack is kept in place on the inner guide (shaft) using one washer at each end. As the shaft moves to one side due to an external displacement, it pushes one washer in the same direction, while the other end washer is kept in place by a peripheral confinement on the housing. The overall motion thus compresses the ring stack. The washers can only move towards the rings to compress them and are otherwise blocked by threaded couplers screwed onto the shaft. This configuration ensures a double acting ring-spring. Hence, regardless of the direction of shaft motion, the ring stack will undergo the same deformation in compression and thus the reaction force of the ring-spring will be symmetric with respect to its initial unloaded position as shown in Fig. 3.

To account for the change in the radial dimension of the rings when the stack is axially loaded, the inner and outer guides are designed such that a small clearance is left between them and the rings. This radial clearance is 0.7 mm between the rings and the outer housing, and 2.0 mm between the rings and shaft. Thus, while the guides are tight enough to prevent misalignment, they provide sufficient clearance to accommodate the deformed ring dimensions when they move axially.

The ring stack within the ring-spring is usually pre-compressed which ensures that the ring-spring behaves like a rigid element for loads lower than a certain threshold. This load defines its pre-load and is quantified as the ratio of peak design force. To add pre-load to the ring-spring, the stack needs to be pre-compressed before mounting onto the hybrid device. This is done prior to screwing threaded couplers on the shaft, by placing extra washers on the ring stack to reduce its nominal length 1. This process can be done to a specific pre-load using a load cell or one based on percentage of spring free length.

2.3. Hybrid device

The hybrid device consists of a parallel combination of the ring-spring and viscous device in terms of input motion and reaction forces. The design of the individual devices was optimised to allow easy integration of the two components. The same clamps (top and bottom) were mounted on the individual devices, as well as the hybrid device during each test.

To enable a parallel setup where each dissipative component undergoes the same input displacement, the housing cylinder of the ring-spring was internally threaded to be screwed on the endcap of the viscous device as shown in Fig. 4. The shafts of the two components were connected using threaded couplers. Thus, as the shaft moves within the hybrid device, the ring-spring displacement will be equal to the piston displacement inside the viscous device.

3. Experimental setup and analyses

3.1. Experimental setup

Experimental testing was carried out on a Material Testing Systems MTS-810 machine. The machine has lower and upper jaws with hydraulic wedge grips that are initially adjusted to hold the test device at its unloaded length. The top jaw grips the top device clamp and remains fixed, and the lower jaw transfers input displacement to the bottom device clamp creating the relative displacement between the two ends of the device, as shown in Fig. 4. Force and displacement sensors are located under the lower jaw to record the ram input displacement and reaction force. This MTS machine has a force capacity of 100 kN and saturation input velocity of ~ 330 mm/s. The data acquisition system recorded force and displacement of the lower ram/jaw at a frequency of