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A HIGHLY-TUNABLE NOVEL ROCKING TUBE DAMPER (RTD)

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Abstract

Self-centering rocking systems with passive energy dissipation devices have been studied extensively in the literature because of their low-damage seismic behaviour and resilience. The rocking mechanism is typically a feature of the structural system, and some form of supplemental energy dissipation system is often added to the structure to absorb energy and limit displacement response.

This paper proposes a new Rocking Tube Damper (RTD) which incorporates a gap opening rocking mechanism into a scalable and non-invasive supplemental damping device. The self-centering rocker is preloaded with a stack of partially compressed conical spring washers. These conical spring washers provide elastic deformation capacity, and together with the applied preload produce a largely bi-linear elastic response that creates an initial resistance to motion and controlled inelastic behaviour.

The RTD has been previously modeled to establish its force-displacement response, showing an ideal bilinear elastic hysteresis with zero residual deformation. A prototype of the self-centering rocker has been fabricated and experimentally tested under cyclic loading. The experimental response matches the broad behaviour expected from the numerical model. However, initial experimental test results exhibited some inherent energy dissipation from friction than was not included within the mathematical model. Suggestions are made for ongoing work to further investigate the full range of response behaviors of the RTD concept.

Keywords: Supplemental damping systems, self-centering dampers, restoring stiffness, rocking structures, passive energy dissipation.

1 INTRODUCTION

Seismic resilience has become an increasingly important design and performance objective for buildings as the earthquake engineering profession seeks to go beyond life safety and design more seismically resilient buildings. The societal impacts of repair and demolition that result from conventional sacrificial capacity design principles are driving the development of supplemental damping systems to reduce damage, expedite recovery and re-occupancy, and support increased resilience of communities to seismic events.

Self-centering dampers that have the ability to minimize or eliminate residual structural displacements are an important option to support seismic resilience. Passive supplemental damping devices that include self-centering mechanisms generally include components such as super-elastic shape memory alloys, are geometry-based, use elastic or viscoelastic materials, and can include some form of rocking mechanism. Table 1 presents a conceptual representation of each self-centering mechanism and the corresponding hysteretic responses.
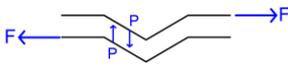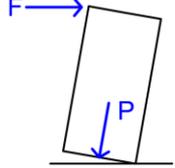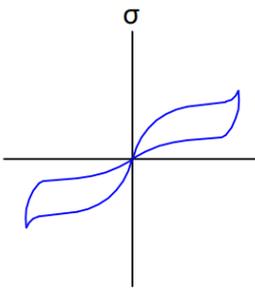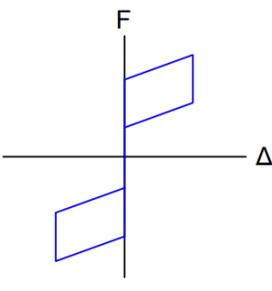
Coupled recentering and energy dissipation		Uncoupled recentering and energy dissipation	
Shape memory alloys	Shape-based	Elastic	Rocking
Recentering provided by martensitic phase transformation.	Recentering provided by device geometry and configuration.	Recentering provided by elastic deformation, including pre-loading.	Recentering provided by gap opening and closing.
Typical SMA hysteretic curve.	Typical flag-shaped hysteretic response of stiff shape-based devices.	Hysteretic curve of elastic devices with low stiffness.	Bilinear elastic response provided by stiff rocking systems.
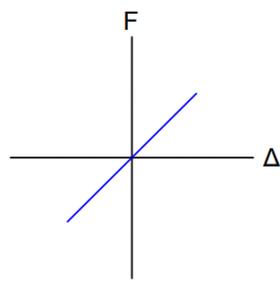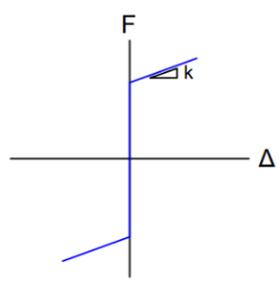
Table 1: Conceptual representation of different recentering mechanisms and the correspond hysteretic response.

Super-elastic shape memory alloys (SMA) dissipate energy and restore their original configuration with unloading, by undergoing a reversible change between the austenitic and martensitic phases of their microstructure [1]. These SMA elements improve energy dissipation and also provide recentering capacity, but they can also be vulnerable to buckling [2] and anchorage failure [3]. As a result of these potential challenges, alternate design concepts have been proposed, including ring-shaped [2,4], SMA ring springs [5-6], U-shaped [7], and SMA disc springs [5]. While this type of SMA-based supplemental damping systems can exhibit a good combination of energy dissipation and self-centering characteristics, these mechanisms are inherently coupled through the material properties, limiting the ability to tune the device to a given application.

Shape-based self-centering dampers provide a recentering behavior through the specific device geometry (Table 1). Generally, they combine conically-tapered ring (friction) springs or wedged plates that have some form of preloaded clamping the plates together. Ring springs comprise alternating conically-tapered inner and outer rings with angled contact surfaces. The spring are compressed under loading and the stored strain energy within the spring elements is released during unloading. The original geometric configuration is restored after loading while energy is dissipated through sliding friction between the adjacent spring elements [8]. Passive self-centering dampers incorporating ring springs have been studied extensively in the literature [8-10]. In addition, researchers have introduced several devices incorporating wedged friction plates and disc springs or conical spring washers (also known as Belville springs), including the Resilient Slip Friction Joint (RSFJ) [11], the Self-centering Rotational Friction Damper [12], and the Self-centering Rotational Joint [13].

While most of these prior devices are linear in their design and are primarily designed to respond to uniaxial loading, Yang et al. [14] proposed a novel Self-centering Conical Friction Damper (SCFD). This device is made up of matching inner and outer conical clamping plates that are preloaded with post-tensioning bolts and conical spring washers. The device is essentially an axisymmetric version of devices such as the RSFJ, and can incorporate simultaneous bidirectional loading. Loading in either orthogonal in-plane direction forces the conical surfaces apart, reacting against the preloaded bolts and creating a reactive force which drives the device to recenter when the load is removed. All of the devices discussed utilize a shape-based recentering mechanism, dictating that the restoring force is inherently coupled to the energy dissipation capacity, resulting in limited tunability and versatility.

The recentering mechanism within rocking systems is created by the dilation from gap opening that occurs between two surfaces that are held together with pretensioned elements, as shown previously in Table 1. Clamping provided by post-tensioning of the elastic elements creates an initial stiff response below a certain threshold of seismic demand. Once this level of demand is exceeded, rocking is initiated, and a lower stiffness is observed due to a combination of rigid body motion and elastic flexure [15]. The combination of these response regimes creates a bilinear elastic restoring force, recentering the structure to its original configuration upon load removal or reversal [16].

Additional work in this area has been undertaken by Hajjar et al [17] and Zhong and Christopoulos [18]. The latter presented comprehensive literature reviews of existing self-centering rocking structural systems and connections. These systems are highly tunable and have reliable self-centering capacities. Although rocking systems are often incorporated at the overall structure-level within low-damage structural systems, to the authors' best knowledge, there are no existing stand-alone damping devices which employ a rocking mechanism to provide self-centering internally within the supplemental damping device.

This paper presents the concept and initial experimental results from a novel self-centering passive supplemental damping device called the Rocking Tube Damper (RTD). This device uncouples the self-centering and energy dissipation mechanisms to enable each component to be individually tuned. A design concept is proposed, and a first prototype is produced and experimentally tested. Specific characteristics of the experimental results are discussed, including deviations between the analytical model and the observed experimental results.

2   SELF-CENTERING MECHANICM

2.1   Device Configuration

The specific design details and overall configuration of a Rocking Tube Damper (RTD) can vary significantly to fit within a particular structural application. However, one possible configuration is presented in Figure 1, where the main subassemblies are presented, including a rocker arm, moving inner core, some form of energy dissipation device, and an outer frame to provide reaction forces and enable input and output forces to be colinear. The rocking arm acts as the self-centering mechanism and pivots about its point of contact with the inner core. This point of contact varies from the top edge or bottom edge of the rocker tube, depending upon whether the overall device is subjected to tensile or compressive loading.

A stack of Belleville conical spring washers is assembled in series and enclosed within the rocker tube. This stack of partially preloaded conical Belville springs provides the elastic deformation capacity and is the source of recentering force during load removal or reversal. The stack of conical washers governs the force and displacement capacities of the RTD. The inner core is free to move axially within the outer frame and transfers the applied load into the rocker tube and the energy dissipation device. The RTD can accommodate various forms or passive energy dissipation devices to create a combined device that is highly tunable due to the uncoupling of the recentering and energy dissipation mechanisms. The energy dissipation device is shown conceptually as a black box in Figure 1 to indicate that the design is not specific type of energy dissipation.
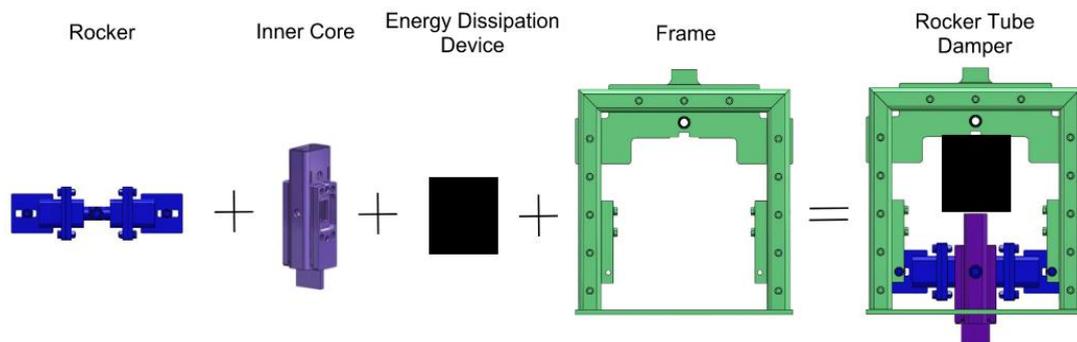

Figure 1: Key components of the overall Rocking Tube Damper concept.

Figure 2 presents a view of the matched pairs of rocker tubes used within this design concept. The inner core of the RTD is omitted within Figure 2 for clarity, but it sits vertically between the two rocking arms. Each rocking tube assembly consist of a rocking base and rocker cap which are bolted together. The rocker bases are preloaded against the inner core, where their preload forces are internally self-reacting within the inner core. The ability to unbolt and separate the rocker base and rocker cap facilitates simpler assembly and accommodates construction tolerances. The tubes are positioned symmetrically about the inner core and connected in parallel, doubling the overall force capacity of the device. While it is not essential to have these rocker arms arranged in symmetrical pairs, this type of symmetrical configuration does simplify design and enables secondary forces to cancel out, eliminating transverse shear forces and promoting uniaxial action.

The reaction plates that are attached the rocker tube cap connect to the outer frame using a slot follower and a pin. This pin and slot follower arrangement facilitates relative lengthening and shortening of the rocker tubes as they dilate during their pivoting action. The rocker tubes contain a high strength threaded rod fitted with a series stack of Belleville conical spring washers. Under a vertically applied load, the rods pivot using a double-shear clevis connected to the inner core using an anchoring pin assembly.

The specific design of the prototype RTD presented in this paper was chosen to enable research purposes, facilitating the testing of a wide range of preloads, Belleville conical spring washer configurations, and different energy dissipation devices and mechanisms. This prototype is intended to act as a proof-of-concept of the RTD idea and does not represent a cost-optimized solution. In practice, the design could be simplified significantly to accommodate one final design configuration for use in a field structure.
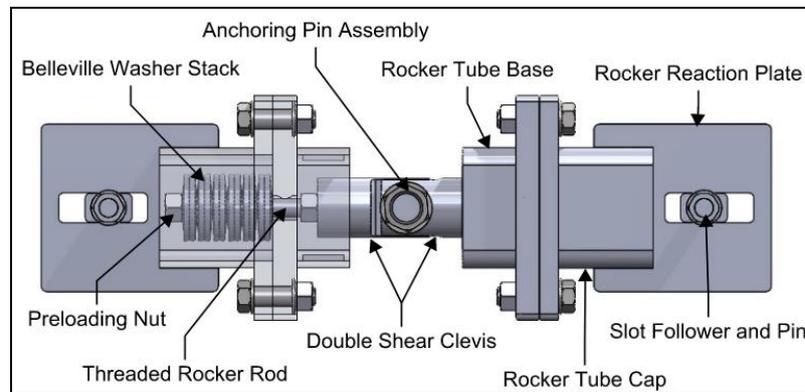

Figure 2: Detailed view of the matched rocking tubes that react against the inner core.

2.2 RTD cyclic response behavior

Figure 3a presents the RTD in its "neutral" or zero-displacement position. In this position the inner core is perpendicular to the longitudinal axis of the two rocker tubes. Under an applied external load denoted as F, the upper tongue of the outer frame remains fixed in position, while the inner core moves relative to the outer frame. When a compressive force is applied to the RTD, the inner core moves upwards through a displacement denoted as Δ relative to the outer frame, and the rocker tubes rock about their lower edges, as shown in Figure 3b. When a tensile load is applied to the RTD and the device is subjected to lengthening displacements, the inner core moves downwards relative to the outer frame, and the rocker tubes rock about their upper edge, as shown in Figure 3c. A detailed mathematical analysis of the reaction mechanisms and a prediction of force deformation behavior of the device is presented in Krieg et al [19]. This current paper focuses on the preliminary experimental results of the prototype device.
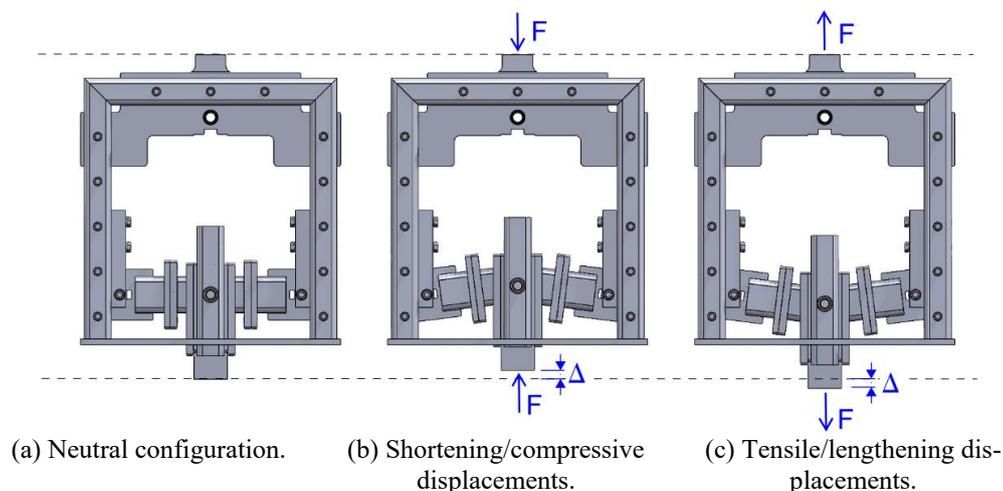

(a) Neutral configuration.   (b) Shortening/compressive displacements.   (c) Tensile/lengthening displacements.

Figure 3: Schematic diagrams showing the RTD prototype (without an energy dissipation device) in different displaced positions.

3 EXPERIMENTAL PROTOTYPE

An experimental prototype was designed and constructed to facilitate experimental testing to prove the concept. The device was designed to fit within the MTS-810 Universal Test Machine at the University of Canterbury with a 100kN force capacity. The overall prototype device is 902mm tall, 720mm wide and has a maximum thickness of 194mm, and was designed for a maximum displacement capacity of ±25mm. The overall weight of the prototype was approximately 165kg, but the outer frame was designed with significant overstrength to enable experimental testing at a wide range of forces. Figure 4 presents the overall prototype design with indicative dimensions, alongside a photo of the prototype.
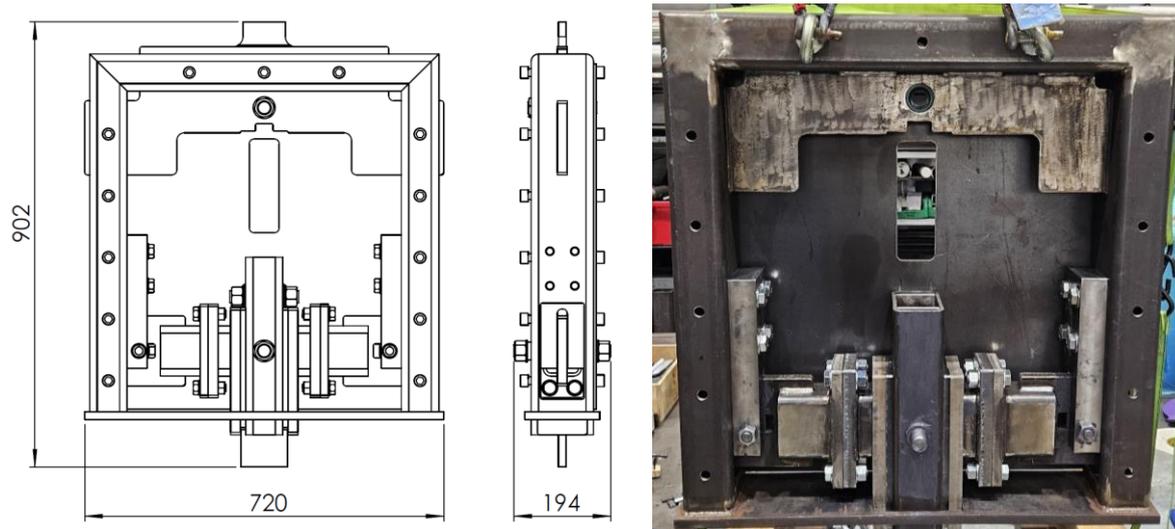

Figure 4: Indicative dimensions of the prototype device and corresponding physical prototype.

In the experimental prototype, the rocker tubes are made from 102mm x 76mm (4" x 3") rectangular hollow section with a wall thickness of 6mm and the longer edge mounted vertically. The horizontal distance from the inner edge of the rocking tube to the line of action of the pin connection between the rocking tube and the outer frame was approximately 212mm. As the preloaded rod and Bellville conical spring washer stack that clamps the rocker tubes to the inner core acts along the longitudinal centerline of the rocker tube, the moment ratio is 212mm to (102mm / 2), or approximately 4:1. This ratio means that the spring stack will compress by approximately one quarter of the vertical displacement imparted into the overall device, and that the resistive force provided by the device from each rocker tube is approximately one quarter of the force developed within the conical washer/spring stack. Due to the presence of two opposing rocker tubes, the total resistive force of the overall device will be approximately one half of the axial force developed within each rocker tube.

The device was assembled with 11 Belville conical springs mounted on each threaded rocker rod. The conical springs were mounted in pairs back-to-back and face-to-face throughout the stack, as shown in the left half of Figure 2. Each Belville conical spring was designed to have 1.433mm of compressive displacement capacity and was designed to go flat at a load of just over 80kN. The overall spring stack has a total displacement capacity of 11 x 1.433 = 15.76mm and a preload displacement of 9.5mm was applied, equating to roughly 60% of the total force and displacement capacity of the spring stack. This preload creates a force demand threshold, below which the device is essentially "locked-up", and rocking will only occur once this force threshold is exceeded. The behavior of the rocking tube damper concept is expected to broadly follow a bilinear elastic backbone, with some inherent energy dissipation through the presence of friction within the moving parts of the device.

4   EXPERIMENTAL RESULTS

The overall RTD prototype under the configuration described in Section 3 was subjected to a range of displacement-controlled fully reversed sine-wave motions. Tests were undertaken at input displacements of ±5mm, ±10mm, ±15mm, ±20mm, ±25mm. Each cycle was conducted at varying frequencies to maintain a constant peak velocity within each cycle of 0.5mm/s. Figure 5 presents a photograph of the prototype device installed within the 100kN capacity Universal Test Machine (UTM).

Figure 5: Photograph of the prototype damper within the MTS-810 Universal Test Machine.

The results of the testing across the varying amplitudes are presented within Figure 6. While a simple analytical model, such as that presented in Krieg et al [19] predicts a bilinear elastic backbone, there is clear evidence of hysteresis and energy dissipation through inherent friction within all the moving interfaces within the device. While this characteristic of the device deviates from an idealized model, the low level of inherent energy dissipation is arguably desirable as it helps to provide supplemental damping to the structure in addition to the recentering/restoring stiffness. The experimental results indicate that the device remains essentially "locked-up" until approximately 15kN due to the presence of preload within the rocking tube spring stacks. Despite the rocking tubes being "locked" during this phase, there is elastic flexibility of the overall device. Beyond this force threshold, rocking begins and the overall stiffness of the RTD reduces markedly, due to the presence of both rigid body motion of the rocking tubes along with further elastic deformation of all the components of the device.

Towards the maximum displacement amplitude of 25mm, there is a notable upward curve in the hysteresis loops. This curve exists as the spring stacks are approaching their flat loads. As the conical spring washers become flat their elastic displacement capacity begins to become exhausted. Once the conical washers flatten, their stiffness increases significantly. The upwards curve seen in Figure 6 is the early onset of this phenomenon.
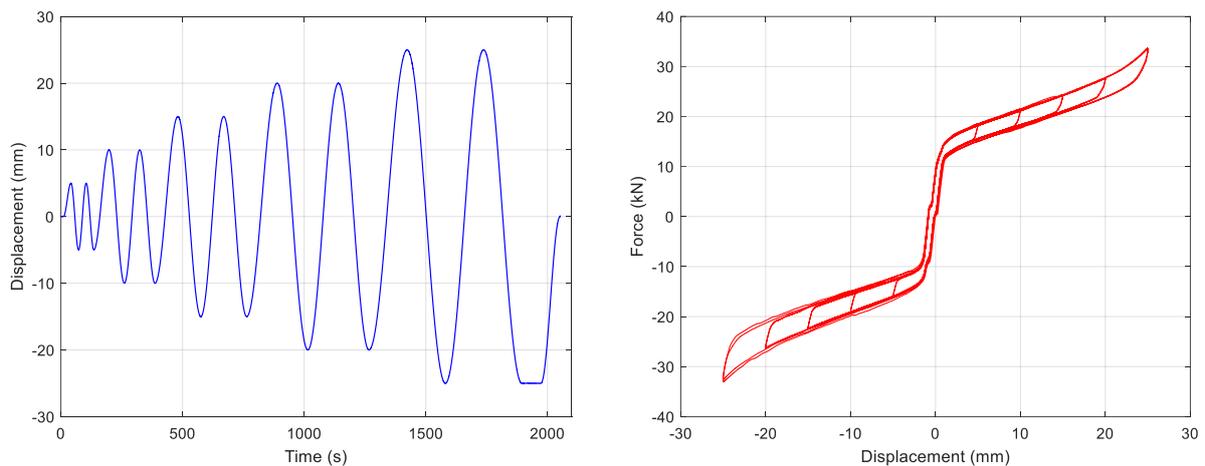
Figure 6: Displacement time-history (left) and RTD hysteretic response (right) from initial experimental testing.

While this paper only presents research on the bare rocking tube damper, it is highly desirable to investigate different types of supplemental damping systems that can be added to the device to act in parallel to the rocking tubes. Good candidate devices include fluid viscous dampers, friction devices, and metallic yielding. It is also desirable to examine a wide range of RTD configurations, including different numbers of conical springs within the spring stack, as well as different preload levels. Ongoing research will further examine and parametrically investigate these additional parameters and configurations.

5 CONCLUSIONS

This paper presents the concept of a supplemental damping system that provides a restoring force using preloaded rocking tubes. This prototype applies the concept of rocking structures but uses this mechanism internally within a supplemental damping device. The concept is discussed alongside the rationale which motivated the design. An experimental prototype was designed and constructed, and initial experimental results are presented which proves that the concept works as intended. Bilinear elastic behavior is demonstrated that includes some hysteresis due to friction within the internal moving components of the device. While peak forces for this initial prototype peak at just above 30kN, the device is easily scalable to much larger applications. Ongoing research is seeking to broaden the testing regime to a wider range of RTD configurations, as well as the inclusion of energy dissipating elements to increase the overall level of damping provided by the device.

ACKNOWLEDGEMENTS

REFERENCES

[1] Qian, H., Li, H., Song, G. (2016). Experimental investigations of building structure with a superelastic shape memory alloy friction damper subject to seismic loads, *Smart Materials and Structures*, 25(12). https://doi.org/10.1088/0964-1726/25/12/125026

[2] Salehi, M., Desroches, R., Hodgson, D., Parnell, T. K. (2021). Numerical evaluation of SMA-based multi-ring self-centering damping devices, *Smart Materials and Structures*, 30(10). https://doi.org/10.1088/1361-665X/ac1d94

[3] Chen, J., Fang, C., Wang, W., Liu, Y. (2020). Variable-friction self-centering energy-dissipation braces (VF-SCEDBs) with NiTi SMA cables for seismic resilience, *Journal of Constructional Steel Research*, 175. https://doi.org/10.1016/j.jcsr.2020.106318

[4] Dong, Y. S., Xiong, J. L., Li, A. Q., Lin, P. H. (2006). A passive damping device with TiNi shape memory alloy rings and its properties, *Materials Science and Engineering*, 416(1–2): 92–97. https://doi.org/10.1016/j.msea.2005.09.079

[5] Fang, C., Yam, M. C. H., Chan, T. M., Wang, W., Yang, X., Lin, X. (2018). A study of hybrid self-centring connections equipped with shape memory alloy washers and bolts, *Engineering Structures*, 164: 155–168. https://doi.org/10.1016/j.engstruct.2018.03.006

[6] Wang, W., Fang, C., Yang, X., Chen, Y., Ricles, J., Sause, R. (2017). Innovative use of a shape memory alloy ring spring system for self-centering connections, *Engineering Structures*, 153: 503–515. https://doi.org/10.1016/j.engstruct.2017.10.039

[7] Wang, B., Zhu, S. (2018). Superelastic SMA U-shaped dampers with self-centering functions, *Smart Materials and Structures*, 27(5). https://doi.org/10.1088/1361-665X/aab52d

[8] Khoo, H.-H., Clifton, C., Butterworth, J., MacRae, G., Gledhill, S., Sidwell, G. (2012). Development of the self-centering Sliding Hinge Joint with friction ring springs, *Journal of Constructional Steel Research*, 78: 201–211. https://doi.org/10.1016/j.jcsr.2012.07.006

[9] Golzar, F. G., Rodgers, G. W., Chase, J. G. (2018). Design and experimental validation of a re-centring viscous dissipater, *Structures*, 13: 193–200. https://doi.org/10.1016/j.istruc.2017.12.008

[10] Issa, A. S., Alam, M. S. (2019). Seismic performance of a novel single and double spring-based piston bracing. *Journal of Structural Engineering*, 145(2). https://doi.org/10.1061/(asce)st.1943-541x.0002245.

[11] Zarnani, P., & Quenneville, P. J. H. (2016). *A resilient slip friction joint* (Patent WO 2016/185432 Al). World Intellectual Property Organization.

[12] Veismoradi, S., Yousef-beik, S. M. M., Zarnani, P., Quenneville, P. (2021). Development and parametric study of a new self-centering rotational friction damper, *Engineering Structures*, 235. https://doi.org/10.1016/j.engstruct.2021.112097

[13] Xu, G., Guo, T., Li, A. (2023). Self-centering rotational joints for seismic resilient steel moment resisting frame, *Journal of Structural Engineering*, 149(2). https://doi.org/10.1061/jsendh.steng-11475

[14] Yang, T. Y., Xu, H. C., Tobber, L. (2020). Mechanism and experimental validation of innovative self-centering conical friction damper, *Structural Control and Health Monitoring*, 27(10). https://doi.org/10.1002/stc.2609

[15] Rodgers, G.W. (2009) Next generation structural technologies: implementing high force-to-volume energy absorbers. PhD thesis, University of Canterbury, Christchurch, New Zealand, http://dx.doi.org/10.26021/1363

[16] Tobber, L., Yang, T. Y. (2021). Seismic design and evaluation of controlled outriggered rocking wall (CORW) using equivalent energy design procedure (EEDP), *Engineering Structures*, 247. https://doi.org/10.1016/j.engstruct.2021.113194

[17] Hajjar, J. F., Sesen, A. H., Jampole, E., Wetherbee, A. (2013). A synopsis of sustainable structural systems with rocking, self-centering, and articulated energy-dissipating fuses, *Department of Civil and Environmental Engineering Reports*. Report No. NEU-CEE-2013-01. Department of Civil and Environmental Engineering, Northeastern University, Boston, Massachusetts.

[18] Zhong, C., Christopoulos, C. (2022). Self-centering seismic-resistant structures: Historical overview and state-of-the-art, *Earthquake Spectra*, 38(2), 1321–1356. https://doi.org/10.1177/87552930211057581

[19] Krieg, S.L., Xu, H., Rodgers, G.W., Tobber, L., (2024) "Development of a Novel Self Centring Rocking Tube Damper (RTD)" Proceedings of the 18th World Conference on Earthquake Engineering, Milan, Italy, June 30th July 5th. https://proceedings-wcee.org/view.html?id=23581&conference=18WCEE