# Newly Developed Passive Damping and Seismic Isolation Devices with Adaptive Post-Elastic Stiffness

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**2017 NZSEE Conference**

**ABSTRACT:** In this paper, a summary of analytical and experimental studies into the behaviour of a new hysteretic damper and a seismic isolator designed for seismic protection of structures is presented. The Multi-directional Torsional Hysteretic Damper (MRSD) and its isolator version MARTI (Multi-Directional Adaptive Torsional Isolator) are patented inventions in which a symmetrical arrangement of identical cylindrical steel cores is so configured as to yield in torsion while the structure experiences planar movements due to earthquake shakings. These new devices have certain desirable properties. Notably, their force-displacement response is characterized by a variable and controllable-via-design post-elastic stiffness. The mentioned property is a result of MRSD's and MARTI's kinematic configuration which produces this geometric hardening, rather than being a secondary large-displacement effect. Additionally, these new systems are capable of reaching high force and displacement capacities, show high levels of damping, and very stable cyclic response. The MRSD and MARTI have gone through many stages of design refinement, multiple prototype verification tests and development of design guidelines and computer codes to facilitate their implementation in practice. Practicality of the new devices, as offspring of an academic sphere, is assured through extensive collaboration with industry in their final design stages, prototyping and verification test programs.

## 1 INTRODUCTION

Major bridge structures when threatened by earthquake hazard, often require especial seismic protection to meet the design objectives of controlled displacement and limited or no damage. This is usually a combination of isolation/dissipation devices integrated into an isolation system for the bridge. While isolators reduce the force demand on superstructure by increasing the effective period and bringing the structure to low-energy region of the design spectrum, energy dissipaters absorb and dissipate part of the energy that has already swept into the structure and reduce the displacement and ductility demand on structural components. However, the added energy dissipation capacity due to addition of energy dissipaters is accompanied by increased effective stiffness owing to the added reaction force of the damper, necessary for it to function. This is an effect in contrast to that of an isolator. Depending on project specifics and design demands, usually an appropriate combination of these two different but complimentary mechanisms is sought to provide an effective design.

The first appearance and application of steel hysteretic dampers during late 60s and early 70s came about as the outcome of a study in the Engineering Seismology Section of the Physics and Engineering Laboratory, DSIR, (Skinner et al. 1993, Kelly et al. 1972, Skinner et al. 1974). Ever since, hysteretic dampers have come under increasing attention as an effective and economical means for response control for important structures. Compared to buildings, deployment of hysteretic dampers in bridges encounters the additional difficulties of multidirectional displacements and presence of service-condition displacements which are not supposed to engage the dampers. Multi-directionality of displacements demands that the device be both mechanically capable of displacement at all planar directions and also providing a uniform response irrespective of displacement direction. Consequently, bridge hysteretic dampers are not as diverse as the building ones. A thorough review of bridge dissipation and isolation devices can be found in (Casarotti 2004). The focus of this paper is a newly developed bridge hysteretic damper, Multi-directional Torsional Hysteretic Damper (MRSD). MRSD is capable of large force/displacement capacities and combination of geometric and material hardening gives it a variable post-elastic stiffness which is believed to be necessary in displacement control of highway bridges. MRSD has passed most phases of necessary analytical and design optimization studies and a 200kN, 120mm-capacity prototype of MRSD has been tested in the laboratory of the Institute of Structural Engineering at the University of the German Armed Forces in Munich (UniBwM) and also in the Mechanics Laboratory of the Engineering Sciences Department at METU. Further experimental investigations with focus on low-cycle fatigue endurance of cylindrical specimens, resembling energy dissipaters of MRSD have recently been completed at the Middle East Technical University (Salem Milani 2014).

## 2 BASIC MECHANISMS AND WORKING PRINCIPLE OF MRSD

MRSD is designed to dissipate energy by torsionally-yielding cylindrical energy dissipaters, named yielding cores. Eight of these identical yielding cores each attached to a torsion arm are arranged in a symmetric configuration to create the MRSD device, as depicted in Figure 1. To convert translational motion of the structure to twisting in the cylindrical cores, each arm is coupled with a guiding rail which through a low-friction slider block guides the motion of the arm. The arms are thus restrained to move along a predetermined path regardless of the direction of the imposed displacement on the rail system relative to the base, creating a guided roller hinge connection. The yielding cores are configured in an upright position around a central column to which they are attached through a thick plate (see Fig. 1 (c)). The plate functions as a diaphragm in transmitting the shear and bending forces imposed by the arms to the top part of the corresponding yielding cores, into the central column, base plate and base anchorage; thus protecting the uniform part of the yielding core below from significant bending and its associated shear force. The uniform part of the yielding cores is where energy dissipation due to torsional yielding occurs.

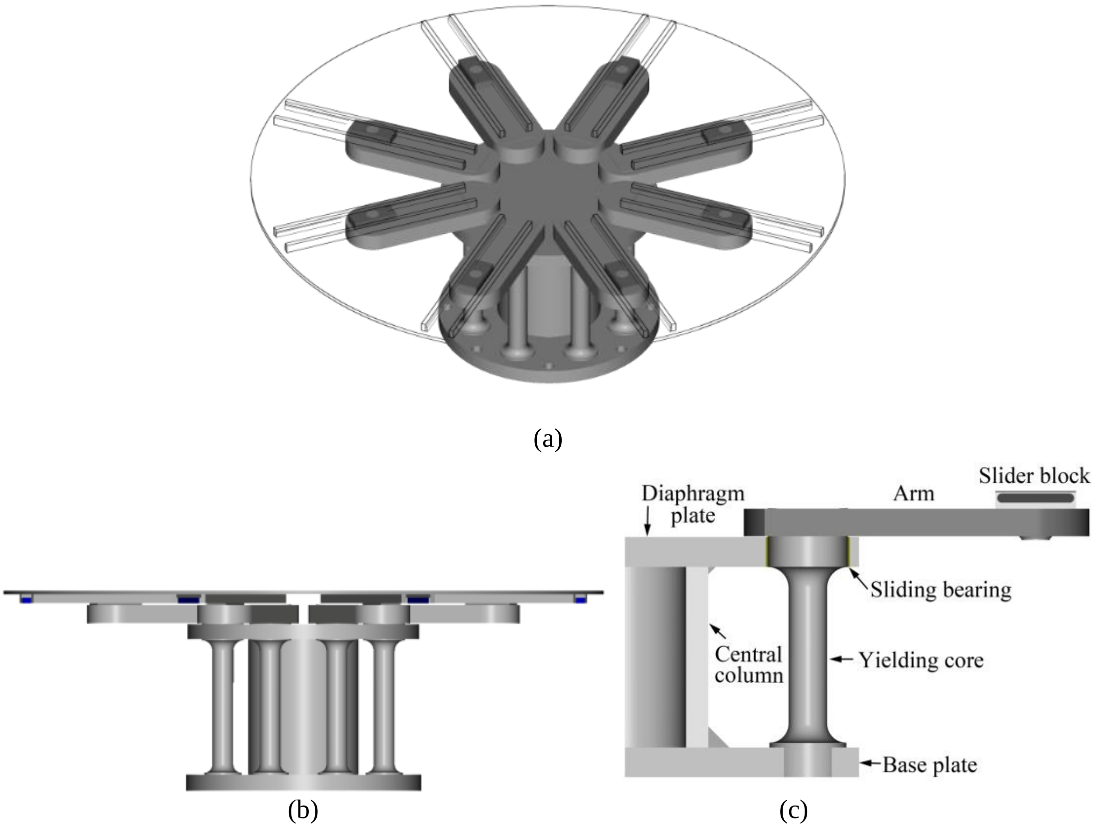



Figure 1. MRSD: (a) Isometric view showing the rail system and base device underneath; (b) side view; (c) energy dissipation unit of MRSD: A yielding core, as attached to other components of the device.

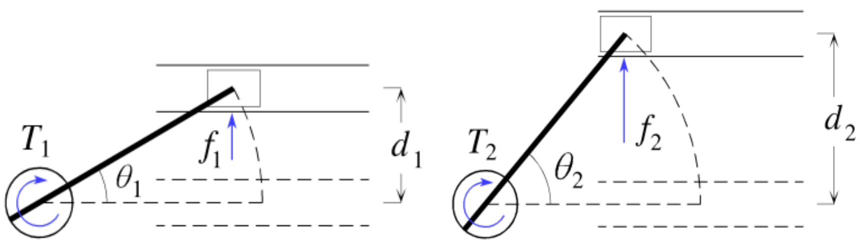
As a general rule in shape design of a yielding dissipater, plasticization and energy dissipation should be obtained at a minimum expense to the device, i.e., plastic straining. The shape should thus be designed to lead to uniform strains over the body of the dissipater and to prevent strain localization. For a dissipater working based on pure torsion, this means a uniform cylinder. However, unwanted bending and shear will upset the desired uniformity in strains and lead to some concentration of strain. Proper functioning of base plate-central column-diaphragm plate as a rigid support for yielding cores against bending is thus crucial to stable and reliable performance of the device. A detailed description of the system is provided in (Salem Milani 2014).

## 3 FORCE-DISPLACEMENT RESPONSE FEATURES OF MRSD

A distinguishing feature in force-displacement response of MRSD is the geometric hardening behaviour which is the outcome of translation-to-rotation motion conversion mechanism in MRSD. As depicted in Figure 2, this mechanism, working at individual energy dissipater level, magnifies the reaction force required to balance the torque in yielding cores. Reaction force of the device is the sum of projections of all eight forces at slider-rail interface. Since the projection angles are independent of displacement and depend only on orientation of rails, the hardening behaviour at eight energy dissipater level directly translates to similar behaviour in global response of the device. The same mechanism also offers the possibility of controlling the desired level of hardening in force-displacement response, through adjustment of the arm length to maximum displacement ratio. This is depicted in Figure 3. Varying levels of hardening obtained as such, leads to hysteresis loops of different shapes as shown in Figure 4; As indicated on these graphs, the parameter used to characterize hardening in MRSD is termed ‘Hardening Index’, defined as:

$$HI = \frac{F_{max}}{F_Y} \tag{1}$$

Where $F_{max}$ and $F_Y$ stand for maximum force and effective yield force of MRSD. Analytical formulation of force-displacement response of MRSD leads to complicated equations unfit for hand calculations (Salem Milani 2014). Nevertheless, simulations have shown that assuming a certain material model for energy dissipaters (steel grade), properly normalized form of force-displacement curves, categorized by their *HI* values, are universal and can be established as the scalable response curves for any MRSD with a specific *HI*, regardless of component dimensions and force/displacement capacity but made of the same steel. Graphs in Figure 4 represent such curves obtained for C45 steel. Furthermore, component friction is found to have negligible impact on the shape of normalized loops and equations for frictionless MRSD can reliably be used to construct the curves.




$$d_2 > d_1 : \theta_2 > \theta_1 : \cos\theta_2 < \cos\theta_1 \quad T_1 \le T_2 \Rightarrow \frac{T_2}{L\cos\theta_2} > \frac{T_1}{L\cos\theta_1} : F_2 > F_1$$

Figure 2. Working mechanism of MRSD responsible for geometric hardening.

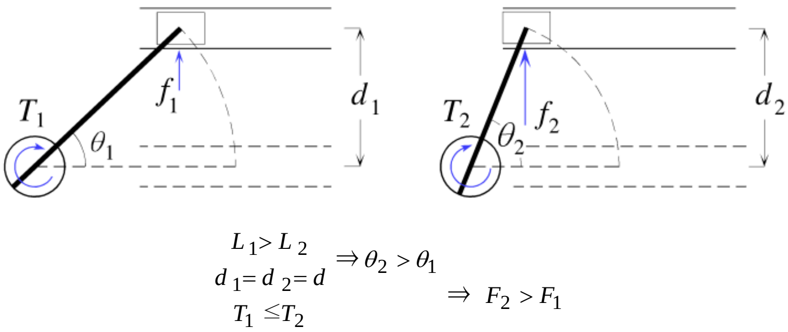



Figure 3. Target hardening index is obtained by adjusting the arm length.

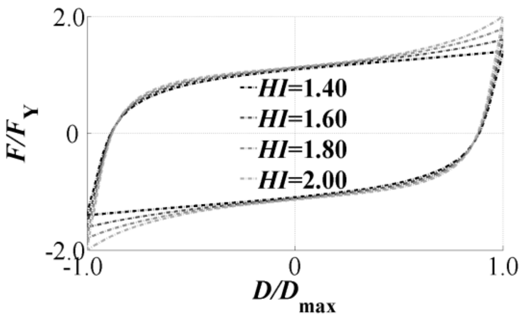



Figure 4. MRSD response for different design hardening indices ($HI=F_{max}/F_Y$): Force (normalized by $F_Y$) versus displacement (normalized by $D_{max}$).

## 4 CHARACTERISTIC PROPERTIES OF MRSD AS RELEVANT TO STRUCTURAL ANALYSIS

Three parameters are necessary and enough to characterize force displacement behavior of MRSD: either ($F_{max}$, $F_Y$, $D_{max}$) or ($F_{max}$, $D_{max}$, $HI$ ). $HI$ ($F_{max}/F_Y$) is used to define the normalized curve (see Figure 4) and $F_{max}$, $D_{max}$ are used as scale factors. In the parameter sets above, yield displacement could be an alternative to $D_{max}$, however, displacement capacity is preferred, being more relevant in design of both the MRSD and the structure, and also a more concretely-defined point on force-displacement curve, as opposed to the effective yield point (see Figure 5). Once a hardening index is chosen by the structural engineer based on requirements of design, geometric properties of MRSD can be easily adjusted to obtain the demanded level of hardening, as indicated in the preceding section and depicted in Figure 3. This is done in design phase of the MRSD itself which follows the structural design of the bridge. The three parameters are therefore enough for the structural engineer to proceed with the design without any knowledge or assumption on design specifics of the device.

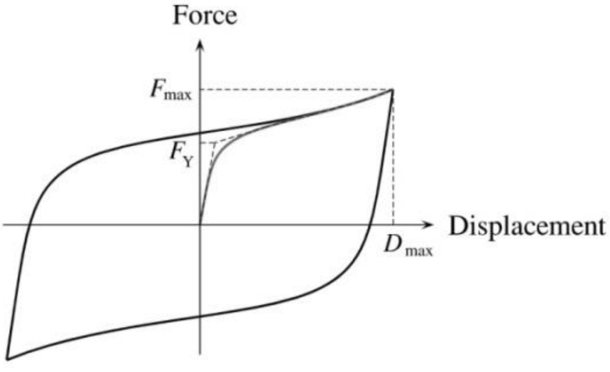



Figure 5. Characteristic properties of MRSD.

# 5 PROTOTYPE TESTING

A 200*kN*, 120*mm*-capacity MRSD was designed for prototype testing, as shown in Figure 6. Since design and configuration of the MRSD allows for easy replacement of the yielding cores (energy dissipaters of MRSD), four sets of replaceable yielding cores were produced out of S355J2+N, C45 (two sets), 42CrMo4+QT steel grades. The device is considered a low-capacity version of its kind, as in real practice a much higher force/displacement capacity devices are employed. Experiments on prototype MRSD, consist of fully-reversed cyclic quasi-static displacement-controlled tests at varying amplitudes, consisting of 1/4, 1/2 and 1.0 $D_{max}$. After completing the test with one steel grade, the eight yielding cores were replaced for the next phase of tests. The most sought-after results in a quasi-static cyclic test on a seismic device are:

- General shape of force-displacement response loops, force measurements, effective stiffness and damping of the device,
- Observations on stability of response expressed in terms of the extent of variation in force-displacement response loops, the maximum force and enclosed loop area at a certain displacement range of response,
- Consistency of measured response with theoretical predictions.

(a) (b) (c)

Figure 6. 200*kN*, 120*mm*-capacity prototype MRSD, as tested at METU: (a) un-displaced position, (b),(c) two extreme strokes of ±120*mm*.

Force-displacement response loops for nearly all of the tests are plotted in separate figures for each type of steel used as energy dissipaters, in Figure 7. The graphs show a very stable cyclic response with little variation in force levels not exceeding %4.0 the mean value at worst which is considerably smaller than %15 limit prescribed by EN-15129, ASCE 07-10 and ASCE 41-06. Higher hardening in the MRSD with 42CrMo4+QT steel and the second set of C45 steel is clearly attributed to higher material hardening, since the rate of geometric hardening is the same for tests with the same displacement amplitudes. Small segments are seen near (force) zero-crossing points with a sharp drop in stiffness. These appear as sloped lines with lower slope than the main unloading branch of the curve and resemble the behavior characteristics of systems with gap. The cause is attributed to the clearances at certain components of MRSD. Lowering manufacturing tolerances will reduce the size of these segments. Table 1 contains the summary of two main properties of the damper, force and effective damping coefficient. The shown values are average of all loops at the specified displacement.

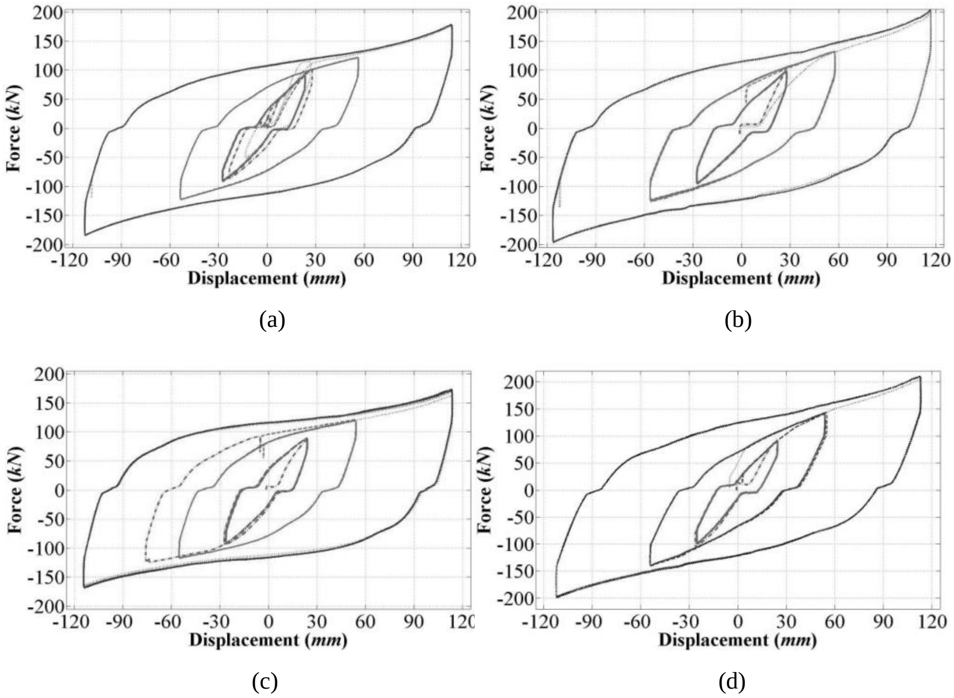



Figure 7. Cyclic response of prototype MRSD with yielding cores made of three different steels: (a) C45-set 1 (b) C45-set 2 (c) S355J2+N (d) 42CrMo4+QT.

**Table 1. Measured maximum force and effective damping coefficient.**

| Steel grade | $D_{max}$ (*mm*) | $F_{max}$ (*kN*) | $\beta_{eff}$ at $D_{max}$ |
|---|---|---|---|
| C45-set 1 | -113,+114 | -184,+178 | 0.33 |
| C45-set 2 | -116,+117 | -196,+204 | 0.33 |
| S355J2+N | -114,+114 | -168,+172 | 0.38 |
| 42CrMo4+QT | -112,+113 | -198,+210 | 0.32 |

## 6 MARTI, AN INTEGRATED BEARING-DAMPER ISOLATION SYSTEM

The concept behind MRSD has been applied recently in development of an isolator/dissipater unit named MARTI, shown in Figure 8. MARTI is an integrated bearing-damper system, composed of a flat slider and four torsional energy dissipation units, similar to those of MRSD. Main advantages of MARTI include:

1. Similar to MRSD, variable post-elastic stiffness in MARTI, diminishes the chances of the isolated structure to get into resonance with the dominant frequency of the ground motion,
2. MARTI causes no elevation change between the isolated interfaces, preventing difficulties in design and functioning associated with such vertical movements (e.g. as in elevator shafts),
3. The impact of environmental or outside physical effects on MARTI is negligible.

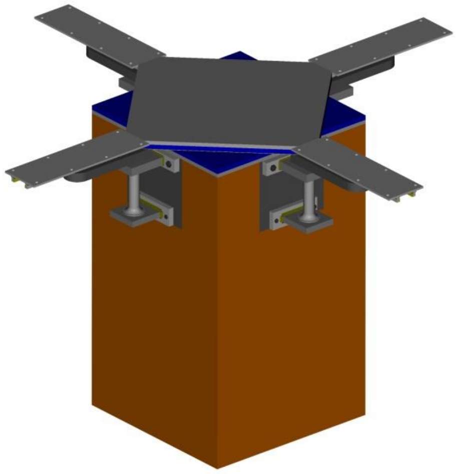


Figure 8. MARTI, an integrated bearing-damper isolation system.

## 7 SUMMARY AND CONCLUSIONS

A summary of analytical and experimental studies into the behavior of a new hysteretic damper, Multi-directional Torsional Hysteretic Damper (MRSD) is presented. A 200*kN*, 120*mm*-capacity version of the device was built and tested in UniBw/Munich and also at METU. The new system is capable of reaching high force and displacement capacities, shows high levels of damping, controllable post-elastic stiffness and very stable cyclic response. A design methodology for the device has also been completed. The concept behind MRSD is applied in development of an isolator/dissipater unit named MARTI.

## 8 ACKNOWLEDGMENT

Full sponsorship of the experimental phase of this work by the international construction firm, MAURER SÖHNE, and the provided technical assistance has been instrumental in success of this research. This contribution is hereby acknowledged. The second author gratefully acknowledges the financial support provided by the Scientific and Technological Research Council of Turkey (TÜBİTAK), under the PhD fellowship program 2215.

## 9 REFERENCES

Skinner, R.I., Robinson, W.H. & McVerry, G.H. (1993). *An Introduction to Seismic Isolation.* Chichester, England: John Wiley & Sons.

Kelly, J.M., Skinner, R.I. & Heine, A.J. (1972). Mechanisms of Energy Absorption in Special Devices for Use in Earthquake Resistant Structures, *Bull. N.Z. Soc. Earthquake Eng.*, **5** (3), pp. 63-88.

Skinner, R.I., Kelly, J.M. & Heine, A.J. (1974). Hysteretic dampers for earthquake-resistant structures, *Earthquake Engineering and Structural Dynamics*, **3** (3), pp. 287-296.

Casarotti, C. (2004). *Bridge isolation and dissipation devices: state of the art review in bridge isolation, structural seismic response and modeling of modern seismic isolation and dissipation devices.* ROSE School, MSc Dissertation.

Salem Milani A. (2014). *Torsional hysteretic damper for seismic protection of structures*. Doctoral Dissertation, Middle East Technical University.