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Analytical and Experimental Investigations of a New Hysteretic Damper for Seismic Protection of Bridges

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ABSTRACT: In this paper, analytical and experimental studies into the behavior of a new hysteretic damper, designed for seismic protection of structures is presented. The Multi-directional Torsional Hysteretic Damper (MTHD) is a recently-patented invention 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. The new device has certain desirable properties. Notably, it is characterized by a variable and controllable-via-design post-elastic stiffness. The mentioned property is a result of MTHD's kinematic configuration which produces this geometric hardening, rather than being a secondary large-displacement effect. Additionally, the new system is capable of reaching high force and displacement capacities, shows high levels of damping, and very stable cyclic response. The device has gone through many stages of design refinement, multiple prototype verification tests and development of design guidelines and computer codes to facilitate its implementation in practice. Practicality of the new device, as offspring of an academic sphere, is assured through extensive collaboration with industry in its final design stages, prototyping and verification test programs. Analytical and experimental progress made so far in this on-going research is summarized in this paper.

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 and Skinner et al. 1975). 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 temperature-induced 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 (MTHD). MTHD 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. MTHD has passed most phases of necessary analytical and design optimization studies and a 200kN, 120mm-capacity prototype of MTHD has recently 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 Engineering Sciences Department at METU. Further experimental investigations which focus on low-cycle fatigue endurance of energy dissipaters are currently in progress in the Middle East Technical University.

2 BASIC MECHANISMS AND WORKING PRINCIPLE OF MTHD

MTHD is designed to dissipate energy by torsionally-yielding cylindrical cores. These are energy dissipater units of the device. Eight of these identical yielding cores each attached to a torsion arm are arranged in a symmetric configuration to create the MTHD 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.

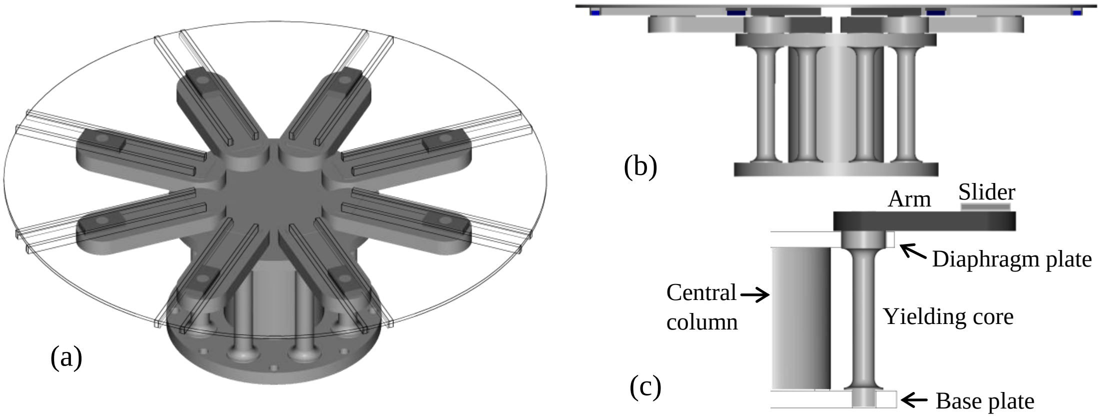


Figure 1. Multi-directional Torsional Hysteretic Damper (MTHD): (a) Isometric view showing the rail system and base device underneath; (b) side view; (c) energy dissipation unit of MTHD: A yielding core.

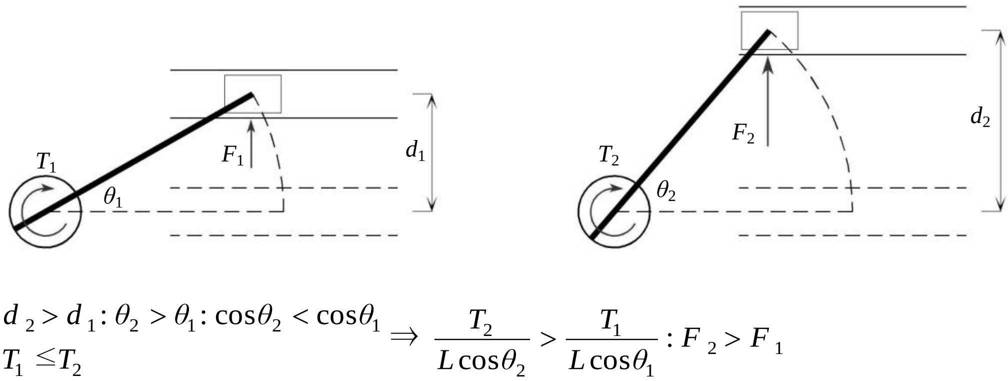
The yielding cores are configured in an upright position around a central column to which they are attached through a thick plate (see Figure 1-c). The plate functions as a diaphragm in transmitting the shear and bending forces imposed by the arms to the top part of the corresponding yielding cores, 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.

As a general rule in shape design of a yielding dissipater, dictated by optimized design principle, plasticization and energy dissipation should be obtained at a minimum expense to the device, i.e., damage, i.e., plastic straining. Assuming that the objective is to minimize the largest strain value irrespective of the extent and distribution, this leads to uniform strain criterion. The shape should thus be designed so as to result in uniform strains over the body of the dissipater. For a dissipater working based on pure twist/torsion, this criterion suggests a uniform cylinder as the optimum shape. As the shape is optimized for pure twist/torsion, unwanted bending and shear will upset the desired uniformity in strains and thus the minimum damage objective, as laid out above. 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 more detailed description of the system is presented in Dicleli and Salem Milani (2010) and Dicleli and Salem Milani (2011).

3 FORCE-DISPLACEMENT RESPONSE FEATURES OF MTHD

A distinguishing feature in force-displacement response of MTHD is the geometric hardening behavior which is the outcome of translation-to-rotation motion conversion mechanism in MTHD. 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 behavior at eight energy dissipater level directly translates to similar behavior in global response of the device.

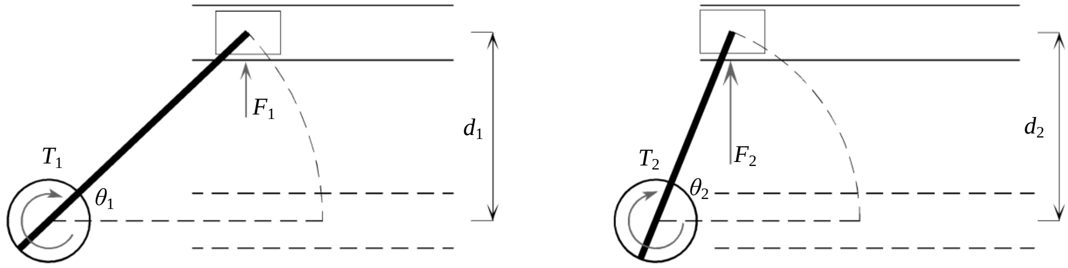
The same mechanism also offers the possibility of controlling the desired level of hardening in force-displacement response, through adjustment of the arm length to maximum displacement ratio. This is depicted in Figure 3.



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

L : Arm length; T : Torque

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



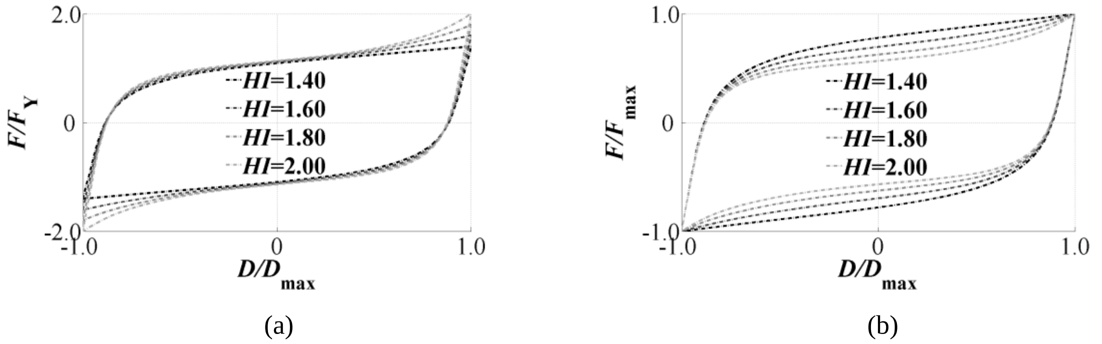
$$\left.\begin{array}{l} \left.\begin{array}{l} L_1 > L_2 \\ d_1 = d_2 = d \end{array}\right\} \Rightarrow \theta_2 > \theta_1 \\ T_1 \leq T_2 \end{array}\right\} \Rightarrow F_2 > F_1$$

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

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 MTHD is termed ‘Hardening Index’, defined as:

$$HI = \frac{F_{\max}}{F_{\mathrm{Y}}} \tag{1}$$

where $F_{\max}$ and F_{Y} stand for maximum force capacity (force at $D_{\max}$) and effective yield force of MTHD. Analytical formulation of force-displacement response of MTHD leads to complicated equations unfit for hand calculations. 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 MTHD 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 MTHD can reliably be used to construct the curves.



(a) (b)

Figure 4. MTHD response for different design hardening indices ($HI = F_{\max}/F_{\mathrm{Y}}$). (a) force values are normalized to F_{Y} to emphasize variation in $F_{\max}$ among loops; (b) force values are normalized to $F_{\max}$ to emphasize shape variation of hysteresis loops among MTHDs designed for the same maximum force.

4 CHARACTERISTIC PROPERTIES OF MTHD AS RELEVANT TO STRUCTURAL ANALYSIS

Implementation of isolation / dissipation devices in practice requires addressing the modeling issues, as arise in the course of structural design. Although quality and accuracy of computer modeling is constantly improving with advancements in computing technology, the kinds of models used in engineering practice are usually simpler than research-oriented models. This can be for the sake of reducing number of input parameters, if nothing else.

In a time history dynamic analysis model whereby the damper is represented by its hysteretic force-displacement rule, usually in form of a phenomenological model, the least parameters necessary to define the model include (elastic stiffness, yield force, post-elastic stiffness) or its equivalent. In case of MTHD, similar number of parameters is necessary and enough to characterize force displacement behavior: 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 MTHD and the structure, and also a more concretely-defined point on force-displacement curve, as opposed to the effective yield point (see Figure 5).

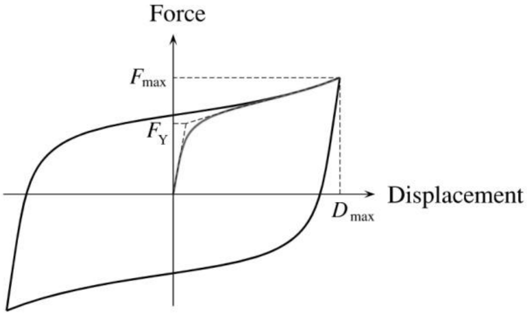


Figure 5. Characteristic properties of MTHD.

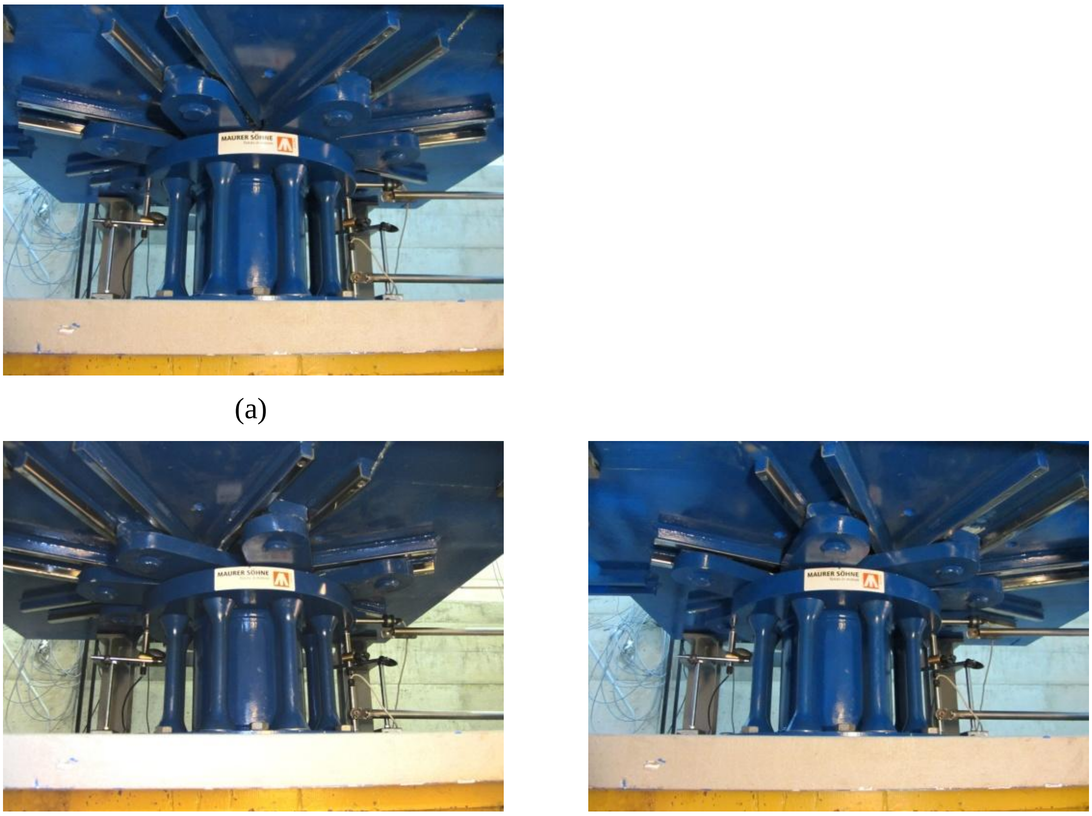
Once a hardening index is chosen by the structural engineer based on requirements of design, geometric properties of MTHD can be easily adjusted to obtain the demanded level of hardening, as indicated in the preceding section and depicted in Figure 3. This is done in design phase of the MTHD itself which 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 itself.

5 PROTOTYPE TESTING

A 200*kN*, 120*mm*-capacity MTHD was designed for prototype testing. Since design and configuration of the MTHD allows for easy replacement of the yielding cores (energy dissipaters of MTHD), 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 MTHD, 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.

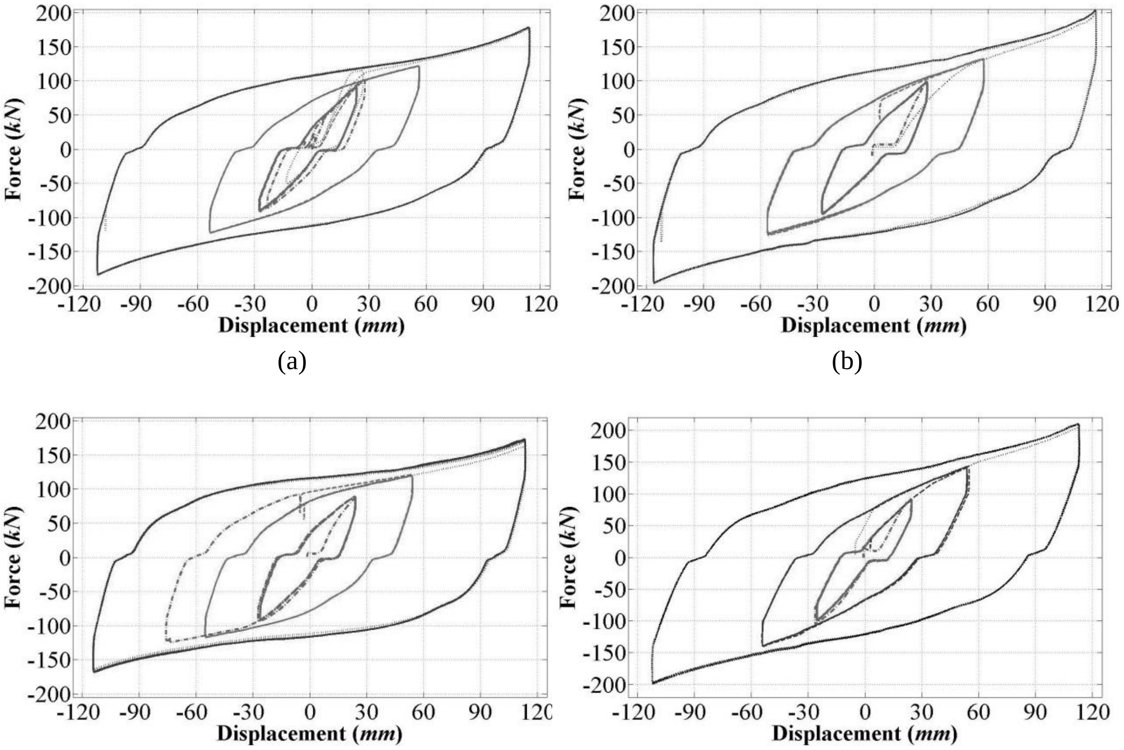

(a)

(b) (c)

Figure 6. 200*kN*, 120*mm*-capacity prototype MTHD, 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, at worst, in force levels not exceeding %4.0 the mean value, considerably smaller than %15 limit prescribed by EN-15129, ASCE 07-05 and ASCE 41-06. Higher hardening in the MTHD 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 MTHD. Lowering of the manufacturing tolerances will reduce the size of these segments.



(a) (b)

(c) (d)

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

Table 1 contains the summary of two significant properties of the damper, the force and equivalent damping coefficient. The shown values are average of all loops at the described displacement. Since separate cyclic tests on steel specimens from which cyclic material characteristics could have been obtained are yet unavailable, an objective comparison between theoretical predictions and experimental results could not have been performed at this stage.

Table 1. Measured maximum force and effective damping coefficient.

Steel grade	D_{max} (*mm*)	F_{max} (*kN*)	β_{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 SUMMARY AND CONCLUSIONS

A summary of analytical and experimental studies into the behavior of a new hysteretic damper, Multi-directional Torsional Hysteretic Damper (MTHD) 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 recently. The work so far, has demonstrated the prospects of the system. To further establish the new device as a technically proven anti-seismic system, and also to optimize the design process of the device, more tests on larger-capacity MTHDs will be required.

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