Improving of Seismic Performance of Steel Structures Using an Innovative Passive Energy Damper with Torsional Mechanism

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Abstract-- **In this paper, a new passive energy damper with torsional mechanism was introduced and studied in numerical and experimental approaches. Experimental results showed a stable hysteresis loop for damper. The requirement recommendations and mathematical formulas to analysis and design was presented. Those formulas have a good accuracy to predict the damper's behavior. Also numerical results indicate that energy dissipation and plastic deformation is concentrated at torsional damper while inelastic behavior and damage of other structural parts and elements are controlled which it enhances structural seismic behavior. It was also concluded that addition of torsional damper, is very economical and easily repairable after an earthquake.**

Index Term-- **Damper; Torsion; Hysteretic behavior; Ductility; passive energy**

I. Introduction

Passive energy dissipation is an emerging new technology that may be used to enhance the seismic performance of buildings [1-3]. The development and characterization of these devices has lead to a seismic design philosophy based upon increasing the energy dissipation capacity of a structural frame as opposed to relying upon increased frame ductility [4-7].

It is important to restore buildings and the functions of the effected urban area as quickly as possible after an earthquake, to overcome these types of problems, a damage-controlled structure has previously been proposed that uses passive energy dissipation devices [8].

The main reason for using passive energy dissipation devices in a structure is to limit the number of damaging deformations in structural components. Among the available varieties of passive energy dissipation devices, the metallic-hysteretic damper is one of the most effective and economical mechanisms for the dissipation of seismic energy input, which is obtained through the inelastic deformation of metallic material. Numerous metallic dampers have been proposed: TADAS [9], the honeycomb damper [10], the buckling-restrained brace (BRB) [11-14], and the slit damper [15-18]. These devices are mainly designed to be incorporated into the bracing system of structural frames. Other devices have been developed to be installed between beams and columns in a frame structure [19-21].

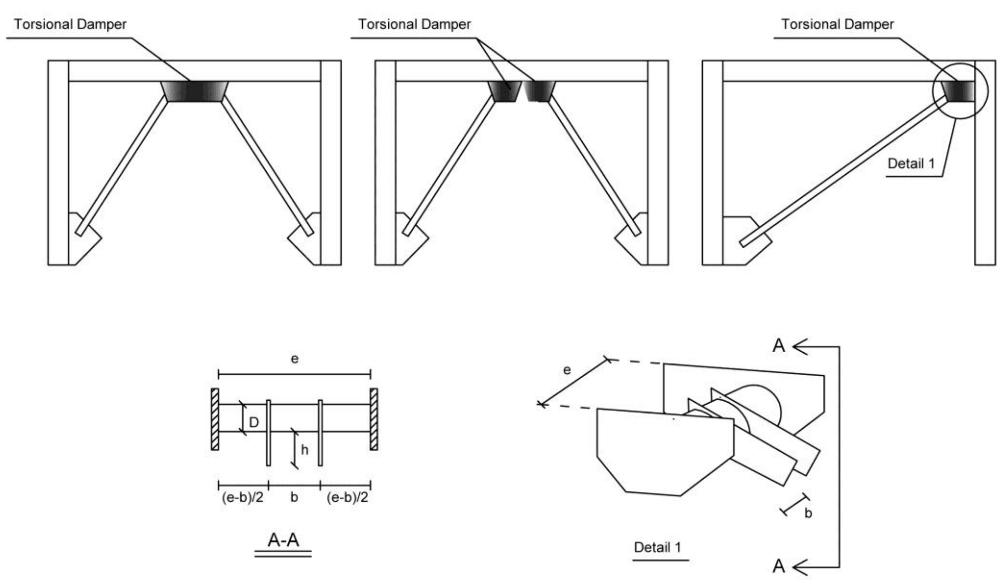

Fig. 1. Sample situation of torsional damper and details

This present study proposes an innovative steel structure that achieves structural performance and it is very economical and easily repairable after an earthquake. The structural configuration and mechanical characteristics of the proposed structural system are addressed in this paper. The main feature of this system is that torsion-plastic deformation is limited in torsional damper. It is possible to limit damage in the torsional damper by designing this damper balance with structural members. So the mechanical behavior of the entire system was evaluated theoretically and mathematical models were formulated to provide stiffness and strength predictions. In the proposed structural system, the mechanical joint was adopted that was equipped with a metallic damper as the diagonal brace member to the boundary frame connection. Fig. 1 shows the sample situation of the torsional damper and details.

II. Torsion performance

When an element subjected to a torque applied, the torque is resisted according to Eq. (1) [22]:

$$T = G.J\frac{d\phi}{dx} - E.Cw\frac{d^3\phi}{dx^3} \qquad (1)$$

Equation (1) represented the internal twisting moment that will develop in the cross section when the member is twisted. The first term represents the resistance of cross section to twist and the second term represents the cross section to warp. From Eq. (1), it can be seen that the warping constant Cw will be zero for thin walled. Here, this section that is originally plane will remain plane after the twisting moment applied [23].

Torsion on a circular shape (hollow or solid) is resisted by shear stresses in the cross-section that very directly with distance from the centroid. The cross section remains plane as it twist (without warping) and torsional loading develops pure torsional stresses only.

The analysis and design of thin-walled (b/t≥10) closed cross-section for torsion is simplified with the assumption that the torque is absorbed by shear forces that uniformly distributed over thickness of element. The general torsional response can be determined from Eq. (2) with the warping term neglected. For a constant torsion moment j the shear stress τ may be calculated as:

$$\tau = \frac{T}{2tA_o} \qquad (2)$$

III. The innovative damper

The design of the torsional damper is performed based on the follows assumption:

- e=b/3
- $\frac{D}{t} \leq 0.45\ \frac{E}{F_y}$
- The angle between the brace member and h is 90 Deg.
- The circular with thin-walled shape is utilized for proposed.
- Von Misses yield theory was used in simulations due to high accuracy in steel materials.

A. Internal forces

The internal forces were idealized as Fig. 2 for predicting the performance of the proposed damper.

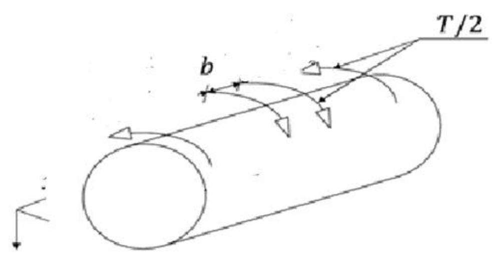

Fig. 2. Internal forces at torsional element

The shear and torsion values are derived as follows. So

$$\begin{cases} V = P/2 \\ T = \frac{P}{2}\,S \\ S = (h + 0.5D) \end{cases} \qquad (3)$$

The bending moment was obtained (Eq.) based on idealization according to Fig.

$$M_{max} = \frac{P}{2}.\left(\frac{e^2 - b^2}{e}\right) \qquad (4)$$

Equating internal and external work per unit length gives:

$$\begin{cases} d\phi_1 / dx = \frac{T.x}{2} \xrightarrow{where} 0 < x < \frac{e-b}{2} \\ d\phi_2 / dx = T/2.(\frac{e-b}{2} + \frac{x}{2}) \xrightarrow{where} \frac{e-b}{2} < x < \frac{e+b}{2} \end{cases} \qquad (5)$$

According equations (5) (they have obtained from Fig. 2), maximum torsion angle are in the two ends of element and under where torque is applied. So it expected that failure is occurred on those places. The places failure is considered in test program.

So the torsion constant is calculated as:

$$j = \frac{4A_0^2}{\int \frac{d_s}{t}} \qquad (6)$$

By using $\emptyset_1 = \emptyset_2$ the performance of the torsional damper is optimization. So the e=b/3 is obtained and the maximum bending moment is modified as followed. So: $M = \frac{8}{9}.P.e.$

B. *Yielding and ultimate strength*

To ensure that the torsional damper operates correctly, it is necessary to have a stable and large energy dissipative capacity. To limit damage to the damper without causing damage to the main structural member, it is necessary for the damper to have relatively yielding ahead of the other structural members.

For predicting the capacity strength of the damper Eq. and Eq. were obtained. Thos formulas were derived with refer to Fig.

$$P_y = \min \begin{cases} \dfrac{0.6\pi.F_y.(D.t)^2}{\beta} \\ \dfrac{\pi.F_y.(D.t)^2}{\sqrt{(e.t)^2+\beta^2}} \end{cases} \quad (7)$$

Where

$$\beta = (h + 0.5D).t + 8D$$

$$P_u = \frac{0.6\pi.F_y.(D.t)^2}{\sqrt{(0.46e.t.F_y)^2+\beta^2}} \quad (8)$$

The P_y, is yielding capacity of the damper. The P_y, was evaluated by combining the shear and torsion.

To made the ultimate strength of the damper (P_u), interaction of bending and shear stress (due to shear and torsion) were considered.

C. *Stiffness*

As shown in Fig. 4, the lateral stiffness of the system made by using the torsional damper was derived from a simple connection model. The torsional damper was modeled into the rotational stiffness.

The lateral shear stiffness of the diagonal brace member (K1) was considered to be significantly stiffness.

$$K_1 = \frac{E.A}{L}.\cos^2\alpha \quad (9)$$

With referring to Eq. and Fig. the torsinal stiffness of the damper (K2) was obtained as follows:

$$K_2 = \frac{6.G.j.S.e}{h}.\cos\alpha \quad (10)$$

Because of series acting of the stiffness diagonal member brace and torsional damper the eqvilent stiffness (K_{eq}) is defined as Eq. .

$$K_{eq} = \frac{K_1 K_2}{K_1 + K_2} \quad (11)$$

$$K_{eq} = \frac{4.8.E.A.G.J.S.e}{A.h.\cos\alpha + 4.8E.S.L.e} \quad (12)$$

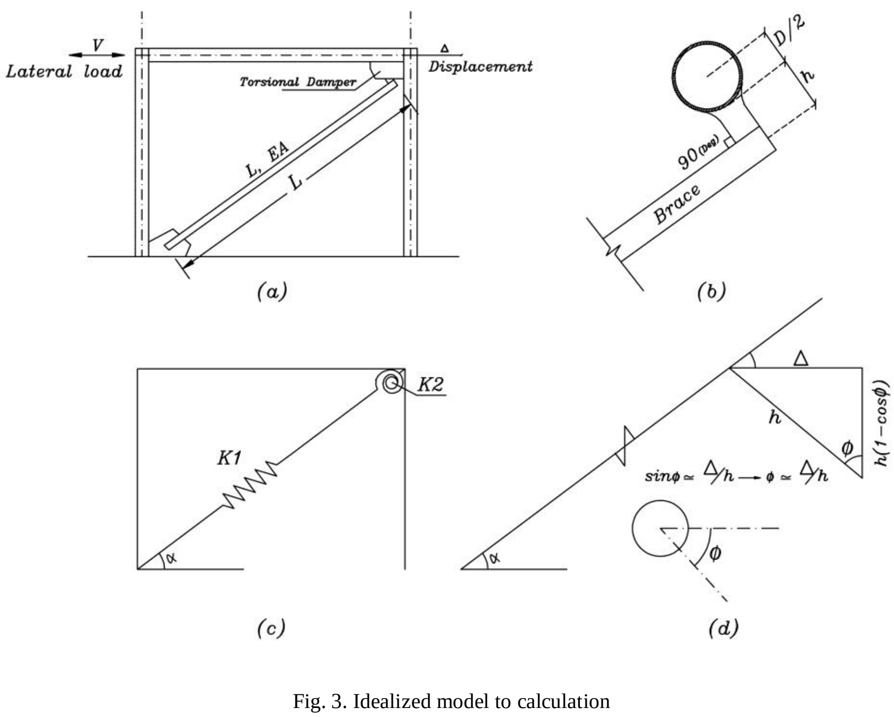

Fig. 3. Idealized model to calculation

IV. NUMERICAL MODELING

The nonlinear analysis of the Finite Element Method (FEM) program by ANSYS software was utilized to investigate the torsional damper. Steel elements were modeled by shell element with 4-nodes and 6 degree of freedom.

To assess the system's post buckling behavior, it was used of the nonlinear large deflection static analysis of the FEM. Convergence criteria were considered for force and displacement values. In incremental nonlinear analysis, initial imperfection proportional to lowest Eigen-mode shape of elastic buckling is introduced to the plates.

V. EXPERIMENTAL STUDY

To consider the torsional element performance, experimental test was performed. To prove the failure place the test were repeated three times. For torsional element was used pipe-section with external diameter 48mm, 3.3mm thickness, and 500mm in length. The detail of specimen test is shown in Fig. 4.

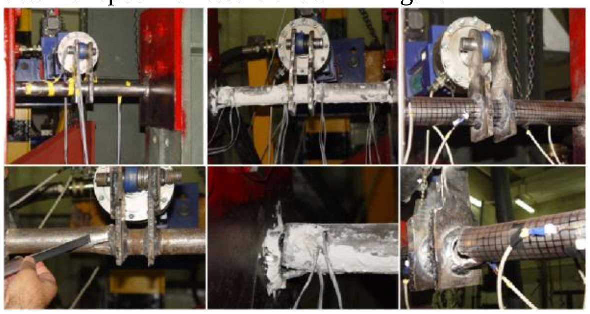

Fig. 4. Test setup and experimental study

The damper was subjected to cyclic loading by applying a very small horizontal displacement to the top of damper. The cyclic displacement was applied according to the loading history, which began with very small values of overall drift which was increased gradually until failure of the damper. The loading history was established according to the specifications for qualifying cyclic tests ATC-24 [24].

In torsional element, one displacement gauges and six strain gauges with cable shield were used to obtain data from element.

A. Experimental results

Fig. 4 shows the test setup and the elements state in the end of test. To consider failure place on torsional element, the testing was repeated tree times. The element’s hysteresis curves did not have differences. It is concluded that failure will occur in one of four parts of element ($x = 0, \frac{e-b}{2}, \frac{e+b}{2}$ or e) because those places the $d\phi / dx = 0$. However, the mathematic predict the four places failure in elements. By the way, the experimental result, prove accuracy of equations (5).

The yielding was started in 25.5 KN force (T=312 KN. Cm) which this results has only 5% error with result of Eq. (7).

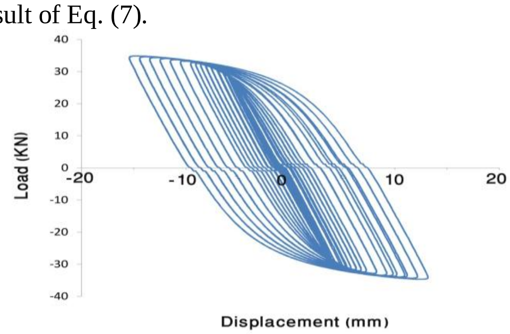

Fig. 5. Hysteresis curve of experimental test

The experimental hysteresis curve of torsional damper is drawn in Fig. 5. It shows an excellent and stable loop of hysteresis curve. This figure shows the height capability of energy dissipation of torsional damper.

VI. NUMERICAL SPECIMENS

First a structure single storey and bay (with single diagonal brace) was designed according to recommendation of AISC [25]. So it was used from 2UNP 100 for diagonal brace, IPB 180 for columns, and IPE 240 for beam. This model was analyzed under cyclic loading. And then the proposed damper was attached and analysis was performed again. A damper was designed as diameter 120mm, thickness 5mm, length 300mm. And this damper was named D12. Two other dampers also were analyzed (D8, D18). D8 and D12 have diameters 80mm (1/1.5 time of D12) and 180mm (1.5 time of D12) respectively. D8 and D12 were selected to consider the system’s behavior when damper are thicker and stronger.

The numerical modeling and the analysis were carried out based on the assumptions given in section 8.

B. Validation and verification of results

To validate numerical modeling procedure, the experimental results were modeled and analyzed using Finite Element Method (FEM). Fig. 6, show a good convergence between the experimental and the FEM results.

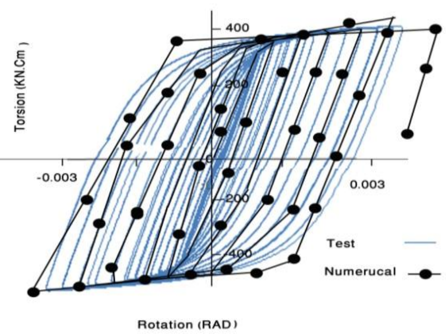

Fig. 6. Comparing the numerical & exprimental test

VII. NUMERICAL STUDY

To verified numerical results, nonlinear analyses were carried out using ANSYS 12. Initial imperfections were considered in analyses proportional to the lowest Eigen-mode shape of elastic buckling and after several trial and error experiments, the optimum finite element method mesh sizing was selected and specimens modeled.

The specimens were subject to cyclic loading. After applying the elastic displacement of, $= \pm \Delta y$ an incremental displacement control was applied, based on $=\pm 2\Delta y, =\pm 4\Delta y, =\pm 6\Delta y$ ect. Here the term of Δ_y is the yielding displacement.

A. Numerical assumptions

The numerical modeling and its calculation is performed with the following assumptions:

- The ductility (μ) values are measured as ultimate displacement divide yielding displacement ratio from the ideal elastic–perfectly plastic curve.
- The elastic stiffness (K) is defined as lateral yielding load divide lateral yielding displacement.
- The over-strength factor (Ω) is the reserved strength value existing between *base shear* corresponding yielding and ultimate base shear.
- No gravitational loading is applied.
- The properties of materials used in simulations are similar to those of the experimental tests.
- Von Misses yield theory was used in simulations due to high accuracy in steel materials.

B. Numerical results

i. Energy absorption

One of the accurate ways of measuring seismic performance of a structure, relies on hysteretic behavior and energy dissipation. In this study, the dissipated energy was measured as the area enclosed in hysteresis loops.

In Fig. 7, present the seven cycles loading versus the displacement (hysteresis loop) obtained from numerical modeling. This figure shows that strength degradation of D8, D12, D18 start in cycle number 7, 6, 4, respectively.

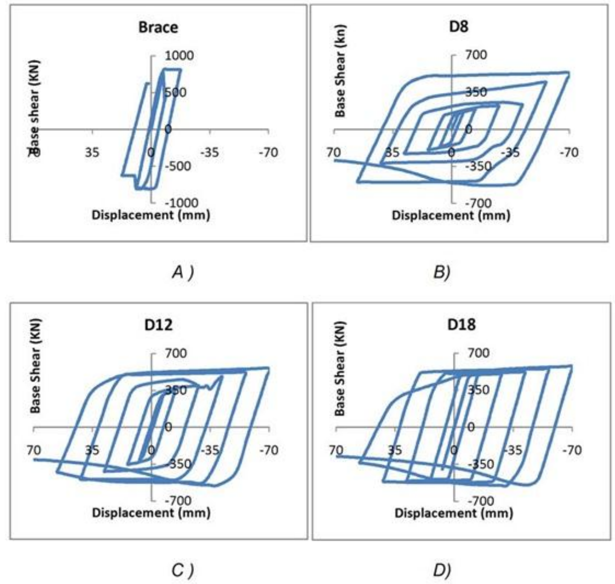

Fig.7. Hysteresis hoops of damper under seven cycles

Fig. 7 shows the dampers hysteresis curves for all cycles. For comparison of the damper behavior, the peak loops of ones are drawn together in Fig. . The area of ones are 178.29, 168.74, 110.03 (KN.m) for D8, D12, D18, respectively. The results show that the D8 models have a better behavior than ones in dissipation energy and stable loops.

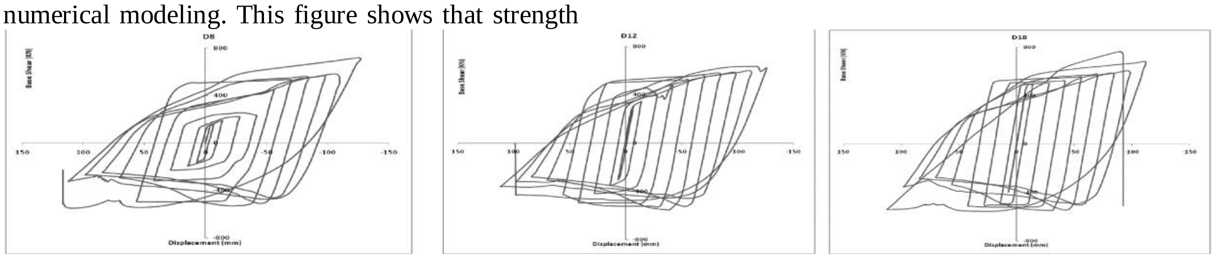

Fig. 8. Numerical results of hysteresis curve

TABLE I
YIELDING INFORMATION OF STRUCTURE

For all of them: V(KN), Δ(mm)	Initial yielding in Damper				Initial nonlinear behavior in diagonal brace				values corresponding failure			
	Tension		Compressive		Tension		Compressive		Tension		Compressive	
	V	Δ	V	Δ	V	Δ	V	Δ	V	Δ	V	Δ
D8	170.3	8.97	167.3	8.97	--	--	--	--	717	126	550	116
D12	331.5	11.3	328.4	12.01	452	92.9	381	89	635.1	126	549.3	112
D18	--	--	--	--	493	12.9	483	12.48	764.6	112	554.3	112

As it can be seen in figures mentioned above, the torsional dampers enhance the energy absorption value.

ii.Damper performance

In order, the D12 is the model that was designed based on part 3 and to D8, D18 was selected to evaluate those formulas. So, values corresponding yielding and failure are listed in Table 1. Results show that in D8 system, nonlinear behavior was concentrated on damper element while the diagonal brace member stands elastically under lateral loading. Also the D18 system does not adequate performance. Because formation plastic hinge is on diagonal brace and the damper element somewhat stand in elastic phase. Yielding and failure of diagonal member after the damper element is the main feature and arrangement of the torsion damper system. The main future was revealed in D12 system with a good amplitude safety. In D12 system, diagonal damper yield on 1.36 times (in tension), 1.16 times (in compression) than damper yielding load. Also the displacement corresponding to yielding of the diagonal brace member occur 8.22 (in tension), 7.41 times (in compression) after torsional damper. The torsional damper delay nonlinear behavior of braced member and the other structural member stand elastically.

According to Table 1 , the damper's diameter is not important affect on ultimate displacement of system.

iii.Stiffness, ductility and over strength

Comparing the over strength and ductility of specimens prove the good performance of this damper.

But yield strength of conventional brace is bigger than one which ultimate displacement and energy absorption and ductility reprisal that.

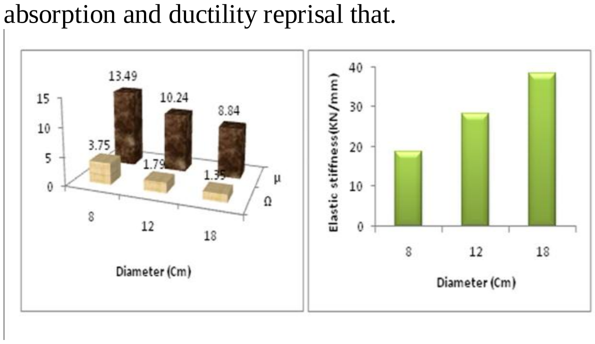

Fig. 9. Structural parameters values

Fig. 9 show values of ductility, stiffness, and over strength. It can be seen that increasing the diameter (torsion constant) of dampers enhance the stiffness but the ductility and over strength is reduced. The values of the stiffness have around 8% error comparing with mathematical formulas. It found that the mathematical formulas were presented in part 2, warrant a good performance of damper behavior.

iv. Damping ratio

It is generally accepted that energy dissipated in cyclic straining of metals is rate-independent. For practical use it is sometimes more preferable to express the device properties in an equivalent viscous system. This is basically a single degree of freedom oscillator with an equivalent stiffness K_{eff} defined as Eq. 13 and see Fig. 10.

$$K_{eff} = \frac{|F_{max}|+|F_{min}|}{|\Delta_{max}|+|\Delta_{min}|} \qquad (13)$$

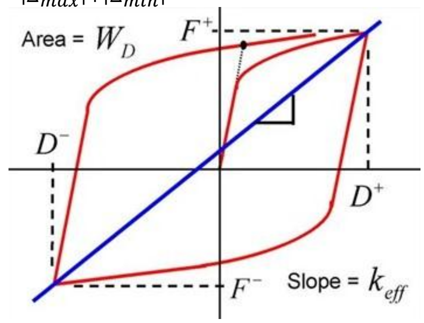

Fig. 10. Idealization of Hysteresis for damping ratio

The damping ratio for the equivalent system, ξeq can be obtained by equating the measured energy dissipated per cycle (ED) in the experiment to that of a viscously damped oscillator [26]. It can be expressed by Eq. (14).

$$\xi = \frac{1}{4\pi}\frac{E_D}{E_{so}} \qquad (14)$$

Where E_{so} is the energy stored in an elastic spring with a stiffness K_{eff} and displacement Δ.

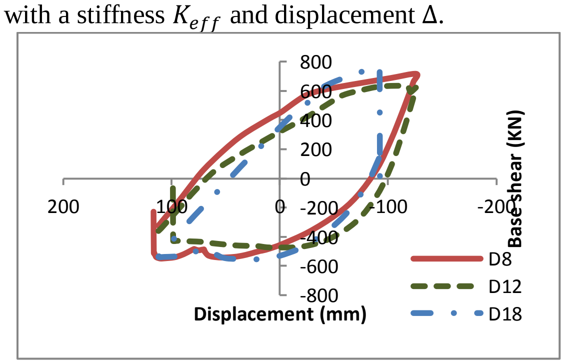

Fig. 11. Envelop hysteresis loops

The damping ratio was calculated for dampers and 36.96%, 38.72%, 23.72% was obtained for D8, D12, D18, respectively. The results were calculated by using Fig. 10.

VIII. CONCLUSION

The conclusions drawn from the experimental and numerical investigations on the innovative torsional damper may be summarized as follows;

1. The innovative torsional damper is very economical and easily repairable after an earthquake.

2. The torsional damper delay nonlinear behavior of the diagonal member brace. So it caused to enhance structural parameter of system.
3. Mathematical formulas have been suggested to design of this system. It found that the mathematical formulas warrant a good performance of damper behavior.
4. The experimental study showed that the torsional damper has an excellent and stable hysteresis loops. Also the mathematical formulas predict in height accuracy on failure places of torsional element.
5. By increasing the damper diameter, the elastic stiffness is increased but the ductility and over strength are decreased.
6. By increasing the diameter of damper degradation strength is started in smaller cycles.
7. The damping ratio was calculated for dampers and 36.96%, 38.72%, 23.72% was obtained.

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