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Analytical Study on Hysteretic Characteristics of Circular Shear Panel Damper

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***Abstract*—This paper aims to investigate a new passive seismic energy dissipating device, circular shear panel damper (CSPD). There are several types of metal-based devices conceived as dampers for the seismic energy absorber whereby damages to the major structural components could be minimized for both new and existing structures. Steel dampers dissipate energy by inelastic deformation. Nonlinear FE simulation was conducted to evaluate the hysteretic behavior of CSPD. Different parameters are considered during analytical evaluation however; diameter-to-thickness ratio (D/t) is the main parameter as it is sensitive in the investigation of hysteresis performance. Depending on these parameters three different buckling shape and hysteretic behavior was found. Generally the CSPD can resist load in a large deformation without strength degradation.**

***Keywords*—circular shear panel damper, large deformation, hysteretic behavior, FE analysis**

I. Introduction

The development and use of passive energy dissipating device to mitigate the risk caused by earthquake has been increased in the last three decades [1,2]. Steel dampers passive energy dissipating device which dissipates seismic energy input to the civil engineering structure from an earthquake through inelastic deformation of metal. The concept and experimental work of metallic energy dissipating device was began by Kelly et al. [1972] and Skinner et al. [1975]. As the development of hysteretic dampers proceeded, two types of dampers using different deformation characteristics of the metal have attracted wide attention: the axial yield type as represented by the buckling-restrained brace (BRB) , and the shear yield type represented by the shear panel damper (SPD). The development and investigation on both types of dampers are also proceeding in recent time [3,4,5]. Passive control systems, also known as passive energy dissipation systems, have been considered an effective and inexpensive way to mitigate earthquake risks to structures because these devices do not rely on external power supply as required by the active energy dissipation devices.

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Circular shear panel hysteresis damper is a type of passive energy dissipating device through metallic deformation of circular shear panel. During an earthquake, a large amount of energy is imparted to a structure. The traditional design approach relies on the energy dissipation as a consequence of inelastic deformation of particular structural zones. The permanent damage of the post-disaster structure is often so serious that it would be expensive to repair, if at all possible [6]. The concept of passive energy dissipation, however, attempts to reduce such permanent damage to the structure. The use of energy dissipative devices installed within a structure large portion of the input energy supplied by wind and/or earthquake can be dissipated whereby damages to the major structural components could be effectively reduced. The role of a passive energy dissipater is to increase the hysteretic damping in the structure [7]. Using dissipating device in structure is alter its stiffness and damping and hence influence its structural response.

In this paper a new concept of steel damper under shear yielding type called circular shear panel damper is developed and its hysteresis characteristics is presented. Non linear FE simulation was conducted for this purpose considering the main parameter diameter-to-thickness ratio of circular panel and circular shear ring. In addition the effect of loading condition, loading protocol, is also reviewed specially for the specimen having stable hysteretic behavior.

II. Background and Applications of CSPD

The use of damper which can be utilized to dissipate seismic energy in civil engineering structures such as building frame and bridge structure is getting popular in recent design scheme. The proposed CSPD relies on the in-plane shear deformation of a thin circular diaphragm steel plate welded inside a circular shear ring (CSR). Like shear panel damper, CSPD can be placed below a structural beam using a V-brace, and between base plate and bridge girder plate as shown in Fig. 1(a) and (b) respectively, so that it automatically comes into play in the event of any horizontal excitation. The CHS serves as a boundary element allowing the tensile strips to be formed and the tension field to be developed following the post-buckling of the thin circular diaphragm plate. As a result of sufficiently large displacements occurring in the circular diaphragm plate, the input energy originating from an earthquake could be dissipated through plastic deformation.

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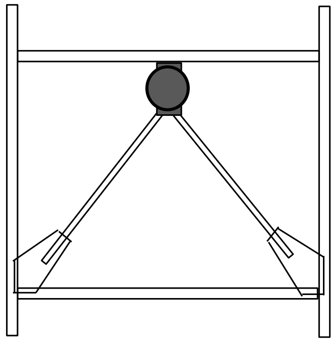
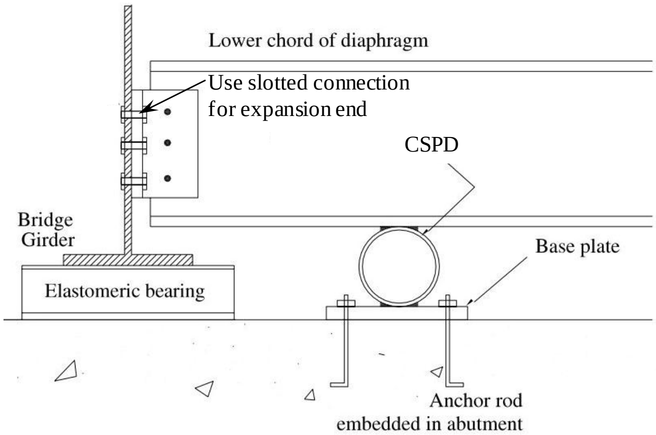


(a).One story frame with a CSPD



(b). Application CSPD for Bridge [9]

Figure 1. Samples of circular shear panel damper incorporated into structures

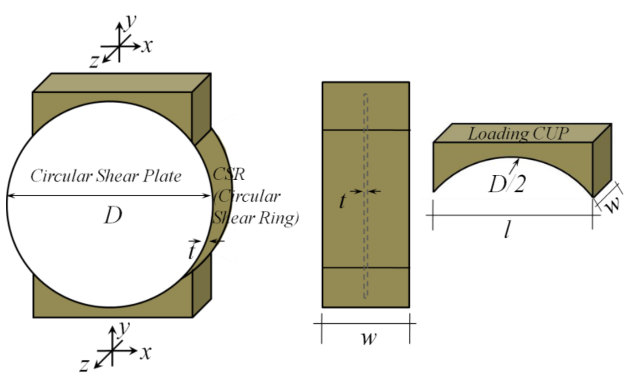


Figure 2. Specimen Detail

III. Non-linear FE Analysis

In order to evaluate the structural performance CSPD was discretized using a three dimensional finite element analysis model called ABAQUS package to evaluate the structural performance of CSP damper. Material nonlinearity was included in the finite element model by specifying a stress–strain curve in terms of the true stress and plastic strain. The engineering stresses and strains obtained from the coupon tests were converted into true stresses and strains for this purpose. Both solid and shell element model have been tried in order to choose the suitable element to simulate the hysteresis behavior. A 3-D shell element S4R quadrilateral elements through mesh generation by Python script is found to be more efficient in modeling CSP damper with linear interpolation and reduced integration are used, as shown in Fig. 3. The structural steel components are modeled as an elastic–plastic material. With elastic and plastic options , the yield and ultimate tensile strength obtained firstly from the results of the coupon tests and then converted into the true stress and plastic strain with appropriate input format for ABAQUS. In the plastic range the important behavior of structural steel to be considered is strain hardening. Thus, mixed hardening (i.e. combined isotropic and kinematic hardening) model was used. Different mesh sizes have been examined as well to determine a reasonable mesh that provides both accurate results with less computational time. The exam results show that, if the mesh is too coarse, a convergence problem will be caused as the contact element was used between the circular hollow section and the endplate surface. However, if the mesh is too fine, the computational time is excessive.

All the translational and rotational displacement components are fixed at lower end plate. A cyclic load was given at upper end plate in Y-direction fixing all the translation and rotation in other direction. The boundary condition and method of loading adopted in the finite element analysis followed closely those used in the tests. A constant strain loading is implemented in which the load is applied by controlling the displacement with the displacement protocol shown in Fig. 4.

The thickness of circular flange and width is 9mm and 50mm respectively. A curved solid rigid body is introduced both ends which have a secant length equal to the radius of circular plate.

TABLE I. ANALYSIS CODE DISCRIPTION

Code	D300t11	D300t10	D300t9.5	D300t9	D300t8.5
[a]D/t	*27.27*	*30.00*	*31.58*	*33.33*	*35.29*
Code	**D300t8**	**D300t7.5**	**D300t7**	**D300t6.5**	**D300t6**
D/t	*37.50*	*40.00*	*42.86*	*46.15*	*50.00*
Code	**D300t5.5**	**D300t5**	**D300t4.5**	**D300t4.0**	
D/t	*54.54*	*60*	*66.67*	*75.00*	

[a]. *w*here: D: is diameter and t: is the thickness of circular panel

IV. Results and Discussions

The von Mises stress contour and deformed shape of analysis specimen having circular shear plate, diameter=300mm and thickness=8.5mm, circular section of D=300 and t=9.0mm is presented in Fig. 5. The hysteresis loop (shear force-inelastic rotation relationship) of the same specimen is also presented in Fig. 6. From the hysteresis loops, the cumulative energy dissipated by the developed device is calculated. It is calculated using equation:

$$E_T = \sum_{i=1}^{n} E_i \qquad (1)$$

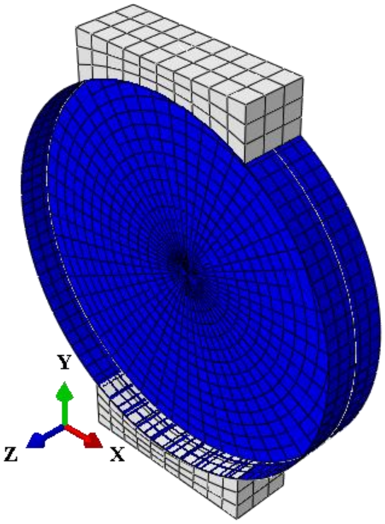
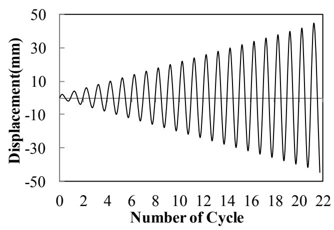
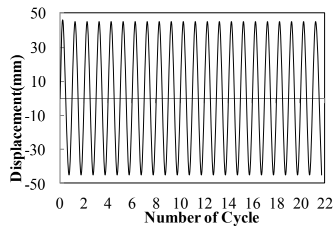


Figure 3. Meshed 3D analysis model

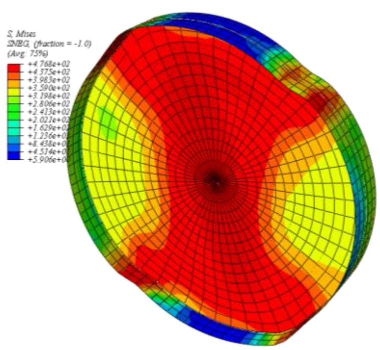


(a) protocol I

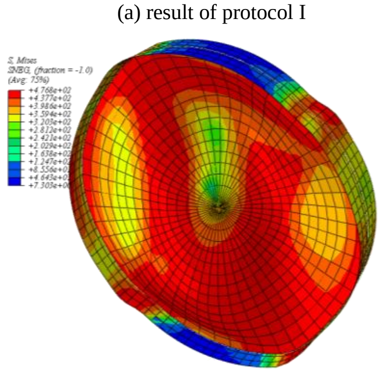


(b) protocol II

Figure 4. Loading protocol



(a) result of protocol I



(b) result of protocol II

Figure 5. Deformed shape of analysis result

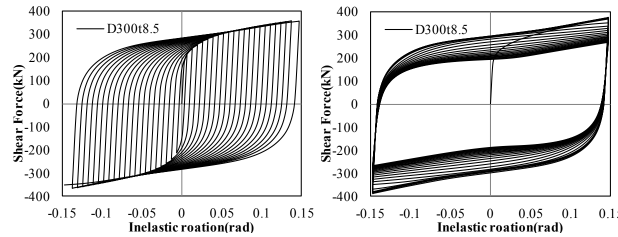


Figure 6. Shear force-Inelastic rotation relationship

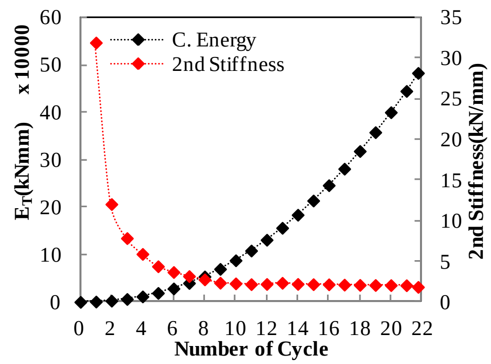


Figure 7. Cumulative energy and 2nd stiffness with respect to number cycle for specimen D300t8.5 protocol I

where: E_T: is the total energy, E_i: energy at cycle i, n: is number of cycle. The calculated cumulative energy and the 2nd stiffness is presented as shown in Fig. 7.

A. *Parametrical Study*

In order to clearly identify and evaluate CSPD the effect of different parameters are studied. The main parameter is D/t ratio of circular plate, it is done by varying the thickness of circular plate keeping constant the diameter and keeping constant the thickness then varying the diameter. In addition, the effect of circular hollow section that used as a flange is also reviewed considering the diameter taking constant length and thickness.

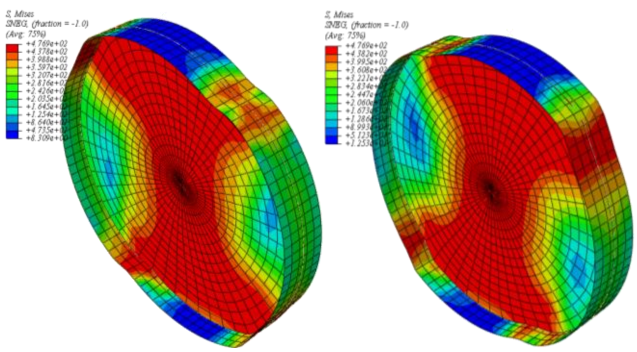
B. *Effect of Diameter to thickness ratio*

The effect of diameter-to-thickness ratio considered in two ways, as stated above, is presented. However, the effect of d/t is sensitive when varying the thickness of circular plate keeping diameter constant. The deformation mode and von Mises stress distribution is shown in Fig. 8 for specimen D/t=20, 28.6 and 40 respectively.

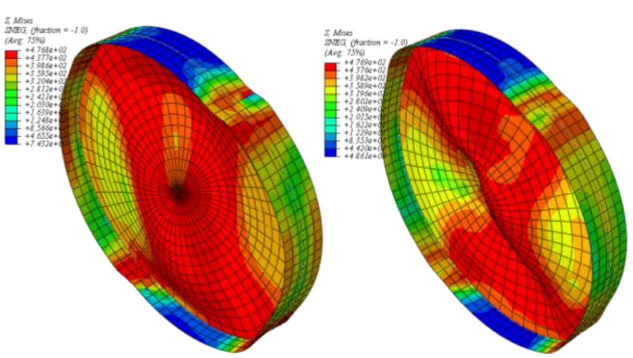
The hysteresis loop of shear force versus shear deformation obtained for different D/t ratio which varies thickness of circular plate is shown in Fig. 7. Three different behaviors are obtained as shown in the Fig. 7: part I is specimen which are yielding prior to buckling without strength degradation Fig. 7 (a). Part II shown in Fig. 7(b) is yielding prior to buckling with strength degradation and Fig. 7(c) which is part III show the yielding with buckling and strength degradation which forms PINCHING at initial displacement. As the thickness decrease the pinching effect become severe. From a total of 16 analysis specimen modeled in this paper for different D/t ratio (for variable thickness) it is found that for specimen having D/t>35.0 was considered as compact specimen in which yielding prior to buckling without strength degradation. 35.0≤D/t≤45.2 was yielding prior to buckling with strength degradation. D/t<45.2 yielding with buckling and strength degradation which forms pinching at initial displacement.

The effect of D/t ratio on initial and second stiffness is presented in Fig. 8. As shown in the figure, both initial and second stiffness decrease as D/t ratio increases.

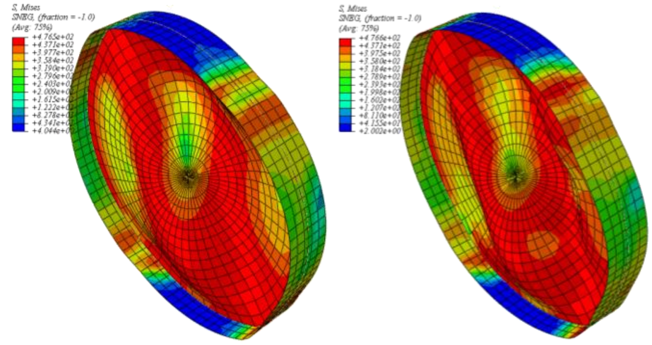
The effect of D/t ratio on initial and second stiffness is presented in Fig. 8. As shown in the figure, both initial and second stiffness decrease as D/t ratio increases. The same effect of D/t ratio is noticed on the cumulative energy and maximum shear force as shown in Fig. 9. However the D/t ratio when the variable is diameter, the effect is not that much sensitive unlike varying thickness. Fig. 10 shows the effect of D/t ratio for varied diameter on cumulative energy and



(a) Type I (D300t10)

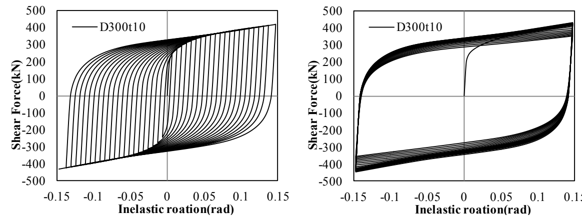


(b) Type II (D300t7.5)

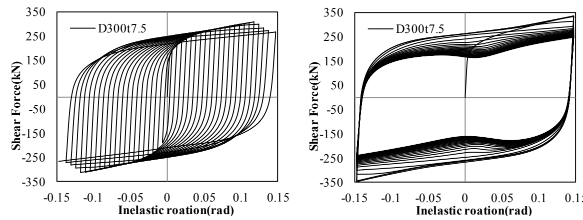


(c) Type III (D300t6.5)

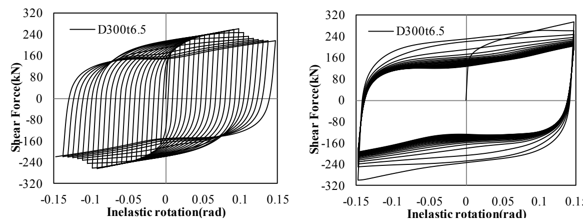
Figure 8. Deformed shape and von Mises stress distribution



Type I



Type II



Type III

Figure 9. Hysteretic shear load-displacement curves non-stiffened CSP damper

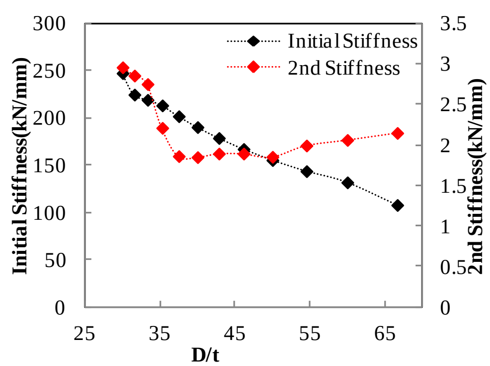


Figure 10. Effect of D/t ratio on initial and second stiffness

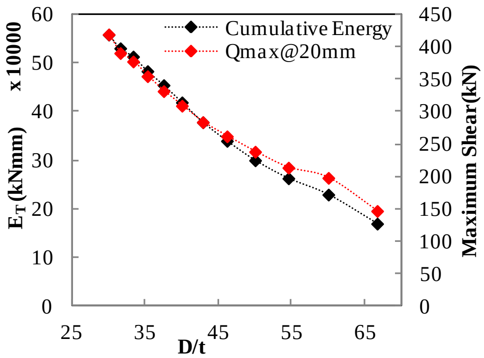


Figure 11. Effect of D/t ratio on cumulative energy and shear capacity

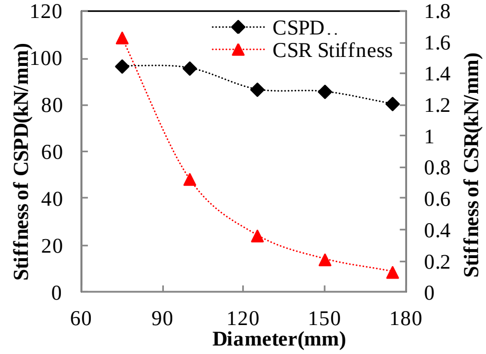


Figure 15. Comparison of initial stiffness of CSR and CSPD

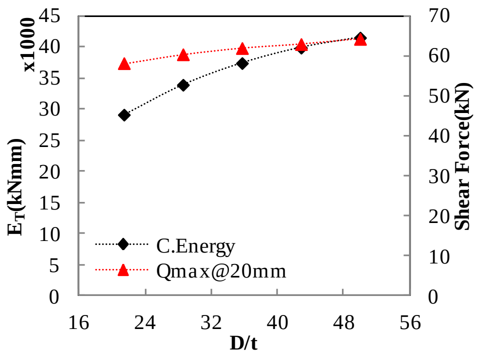


Figure 12. Effect of D/t on cumulative energy Q_{max}

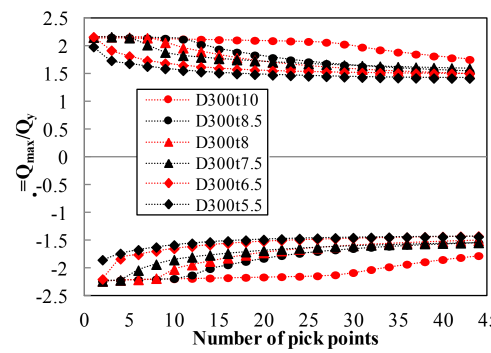


Figure 16. Relationship between load increment ratio to numbers pick points

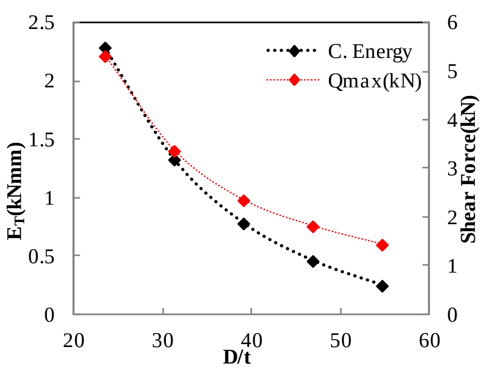


Figure 13. Cumulative energy and shear capacity of CSR

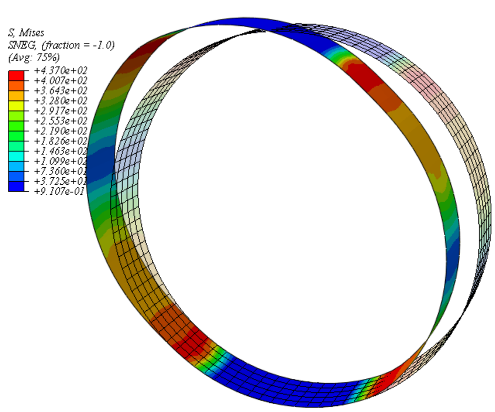


Figure 14. Deformed shape and von Mises stress distribution of CHS

maximum shear force at 20mm displacement. As we mentioned, the effect of D/t ratio for varied diameter is not sensitive compared to varied thickness as comparing Fig. 9 and Fig. 10.

C. *Effect of CSR (circular Shear Ring)*

The von Mises stress contour and deformed shape of analysis specimen CSR without circular plate of having diameter=100mm and thickness=3.5mm is presented in Fig. 12. The energy absorption capacity and shear capacity of circular hollow section without a thin circular diaphragm is presented in Fig. 11 with variable diameter. The comparison of change in stiffness CHS and CSPD is presented in Fig. 13. The effect of CHS on cumulative energy absorption, initial stiffness and shear capacity is 5.12%, 1.66% and 6.73% respectively.

D. *Effect of Loading Protocol*

In order to examine the effect of loading protocol on analysis specimen with different D/t ratio by varying the diameter is considered. The size of analysis specimens are D300tx (where D:is the diameter which is constant value 300mm, t: thickness of circular diaphragm plate and x: the value thickness which 4-11mm in this case). The purpose of evaluating the effect of loading protocol is to determine the strength degradation specially for stable (Type I) CSP damper at constant maximum displacement and the rate at which the shear force resisting capacity of CSPD decreases. The comparison of loading response of the loading condition is presented in Fig. 9 for three different hysteretic behavior, Type I, Type II and Type III. From Fig. 16 one can notice that, for Type I specimen, the hysteretic behavior in the first loading condition is stable however when apply the second protocol the response is different, the shear resisting capacity decreases as the number of cycle increase such as specimen D/t=35.29

The load increment ratio of analysis model is calculated for the response of Fig. 4 (b) in the constant displacement loading protocol. The load increment ratio is given by:

$$\xi = \frac{Q_{MAXi}}{Q_Y} \quad (2)$$

where: • : load increment ratio, Q_{MAXi}- is the maximum shear force at each pick points, Q_Y: yielding shear force.

The calculated load increment ratio versus the number of pick points is plotted in Fig. 16. As shown in the Fig. 16, the increment ratio decreases as the D/t ratio increases. The decreasing rate of Type III CSPD is high compared to Type I and Type II.

V. Conclusion

This study evaluates the structural performance of circular shear panel damper. Different parameters has also been considered. Diameter-to-thickness ratio (D/t) has significant and sensitive effect on the hysteretic behavior, maximum shear resisting capacity and hence cumulative energy. When the D/t decreases the shear resisting capacity increases and the hysteretic behavior become to stable. From the hysteretic behavior, CSP damper with stable hysteresis behavior or specimen that deform without strength degradation at large deformation has most likely to be used as passive energy dissipating device in civil engineering structures.

Acknowledgment

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