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Analytical Evaluation on Hysteresis Performance of Circular Shear Panel Damper

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Abstract**—**The idea of adding metallic energy dissipaters to a structure to absorb a large part of the seismic energy began four decades ago. 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. This paper aimed to develop and evaluate structural performance of both stiffened and non stiffened circular shear panel damper for passive seismic energy protection by inelastic deformation. Structural evaluation was done using commercially available nonlinear FE simulation program. Diameter-to-thickness ratio is employed as main parameter to investigate the hysteresis performance of stiffened and unstiffened circular shear panel. Depending on these parameters three different buckling mode and hysteretic behavior was found: yielding prior to buckling without strength degradation, yielding prior to buckling with strength degradation and yielding with buckling and strength degradation which forms pinching at initial displacement. Hence, the hysteresis behavior is identified, specimens which deform without strength degradation so it will be used as passive energy dissipating device in civil engineering structures.

Keywords**—**Circular shear panel damper, FE analysis, Hysteretic behavior, Large deformation.

I. Introduction

THE concept and experimental work of metallic energy dissipating device was began by Kelly in 1972 [1] and Shinner in 1975 [2]. From this period of time, considerable attention has been paid for research and development of structural control devices, particularly steel damping devices. These devices are developed with particular emphasis on alleviation of wind and seismic response of buildings and bridges. 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). Recently, the development and evaluation on both types of dampers are under investigation [3]-[6]. These dampers are categorized as passive control systems. Passive control systems, also known as passive energy dissipation systems, have been considered as 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 [7].

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A circular shear panel hysteresis damper is a new steel damper. It 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 [8]. 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 [9], [10]. Using dissipating device in structure alters its stiffness and damping and hence influences its structural response.

The hysteresis performance of passive dissipating device is given much attention because studies shows that the efficiency of these device [11]. Many researchers use experimental and analytical approach in order to evaluate passive energy dissipating device. A continuous Bouc-Wen's model [12] is commonly used by researchers to model the inelastic behavior of passive devices. In this paper, non linear FE simulation was conducted to evaluate a new concept of steel hysteresis damper under shear yielding type called circular shear panel damper. The simulation was conducted considering diameter-to-thickness ratio of circular panel and arrangement of stiffeners as a main parameter.

II. Development of Circular Shear Panel Hysteresis Damper

The use of damper which can be utilized to dissipate seismic energy in civil engineering structures such as building frame and bridge structure is becoming common in recent design procedure. 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 Figs. 1 (a) and (b) respectively, so that it automatically comes into play in the event of any horizontal excitation. The CSR 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

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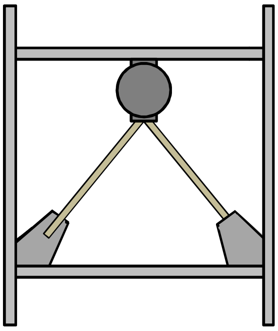
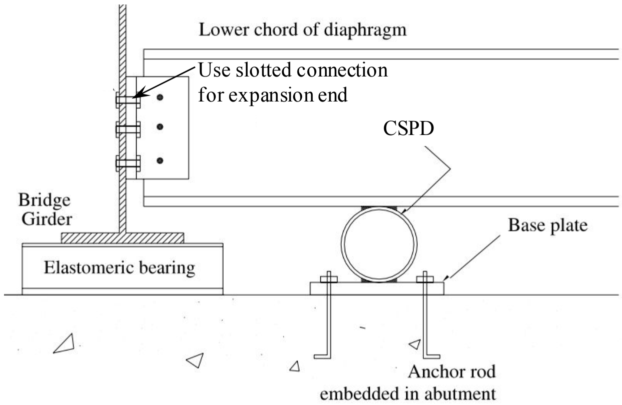
earthquake could be dissipated through plastic deformation.



(a) One story frame with a CSPD



(b) Application CSPD for Bridge [13]

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

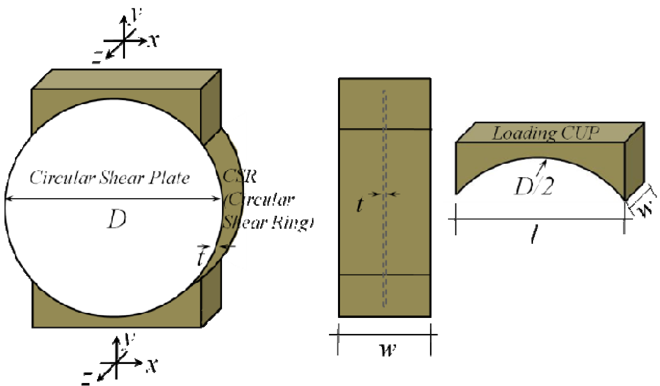


Fig. 2 Specimen Detail

III. Nonlinear FE Analysis

A. Material Modeling

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 3D shell element called 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.

The analysis specimen is composed of circular plate, circular shear ring and longing cup. It is coded like D300t8: means diameter 300mm and thickness 8mm.

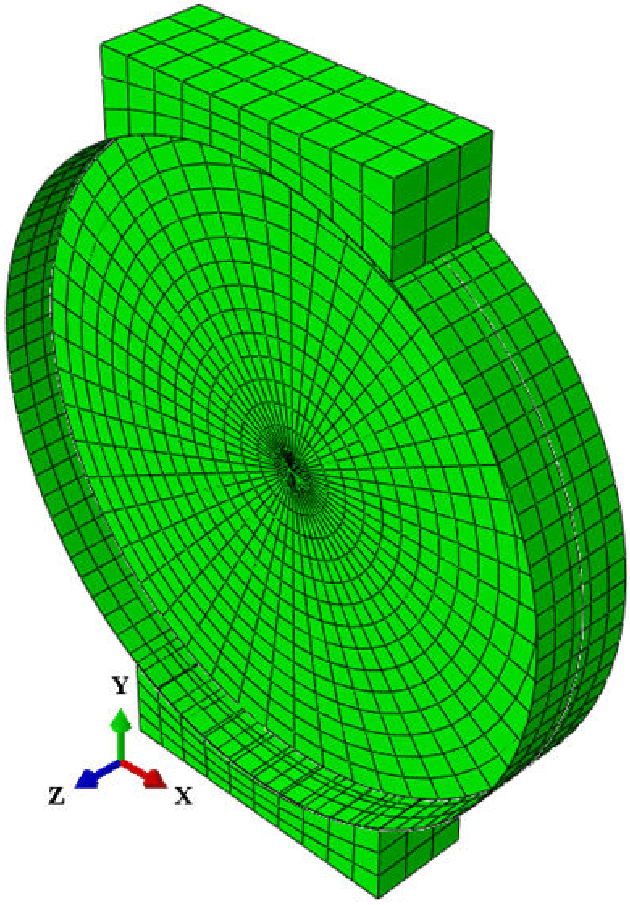


Fig. 3 3D analysis model

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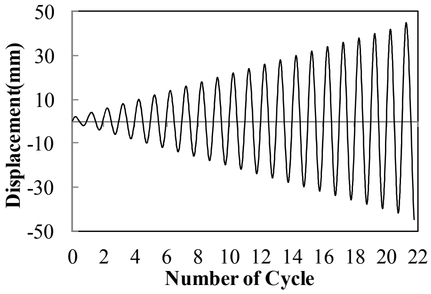

Fig. 4 Loading protocol

B. Load Protocol

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 CHS and length is 3.2mm and 50mm respectively. A curved solid rigid body is introduced both ends which have a secant length of equal to the radius of circular plate.

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, width w=50mm 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 and the second stiffness is calculated. The cumulative energy and second stiffness is expressed as:

$$E_T = \sum_{i=1}^{n} E_i \tag{1}$$

$$K_2 = \frac{Q_{\max_i} - Q\min_i}{U_{\max_i} - U_{\min_i}} \tag{2}$$

where: E_T: is the total energy, E_i: energy at cycle i, Q_{maxi}: and Q_{mini} is the maximum and minimum shear force at each cycle i respectively, u_{maxi} and u_{mini}: is n: is maximum and minimum displacement at each cycle i respectively, number of cycle. The calculated cumulative energy and the 2^{nd} stiffness is presented as shown in Fig. 7.

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.

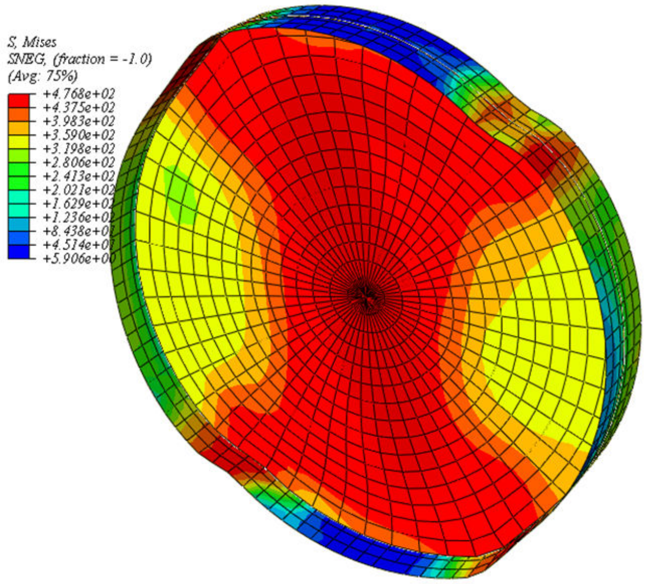

Fig. 5 Deformed shape of analysis result

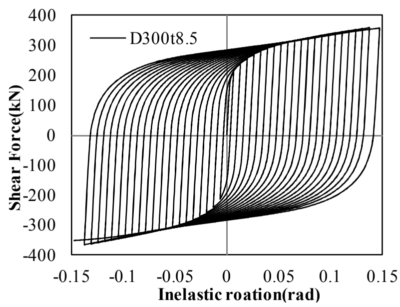

Fig. 6 Shear force-Inelastic rotation relationship

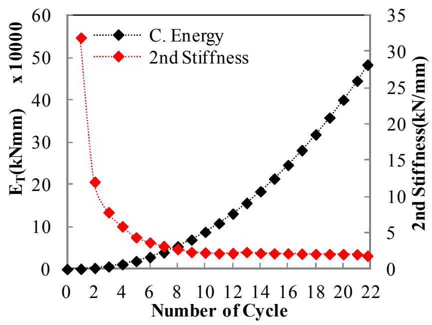

Fig. 7 Cumulative energy and 2nd stiffness with respect to number cycle for specimen D300t8.5 protocol I

A. Effect of Diameter-to-thickness ratio of Circular plate

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. So, in order to evaluate the effect of D/t ratio, we used D (diameter)=300mm and vary t (thickness)= 5-10mm. The deformation mode and von Mises stress distribution is shown in Fig. 8 for specimen D/t=30, 40 and 46.15 or D300t30, D300t7.5 and D300t6.5 respectively.

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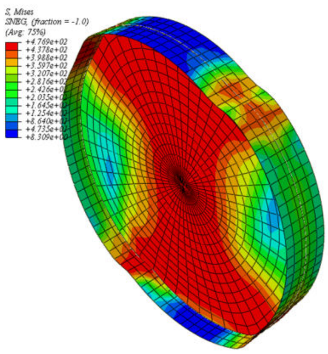
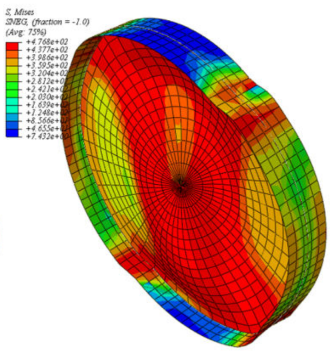
The hysteresis loop of shear force versus shear deformation obtained for different D/t ratio which varies thickness of circular plate is shown in Fig. 9. Three different behaviors are obtained as shown in the Fig. 9: part I is specimen which are yielding prior to buckling without strength degradation Fig. 9 (a). Part II shown in Fig. 9 (b) is yielding prior to buckling with strength degradation and Fig. 9 (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>23.5 was considered as compact specimen in which yielding prior to buckling without strength degradation. 23.5≤D/t≤29.9 was yielding prior to buckling with strength degradation. D/t<29.9 was yielding with buckling and strength degradation and 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.

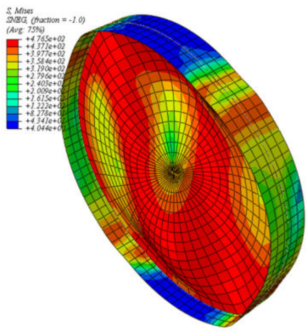
The effect of D/t ratio on initial and second stiffness is presented in Fig. 10. As shown in the figure, both initial and second stiffness decrease as D/t ratio increases. The same effect of D/t ratio is noticed on the cumulative energy and maximum shear force as shown in Fig. 11. The effect of D/t ratio when diameter is variable and thickness kept constant is not that much sensitive like thickness is variable and diameter kept constant.



(a) Type I (D300t10)

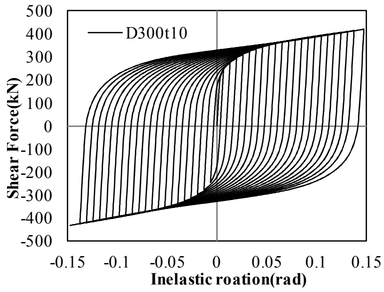


(b) Type II (D300t7.5)

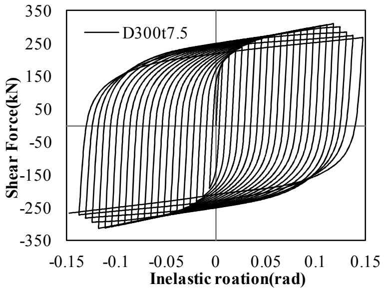


(c) Type III (D300t6.5)

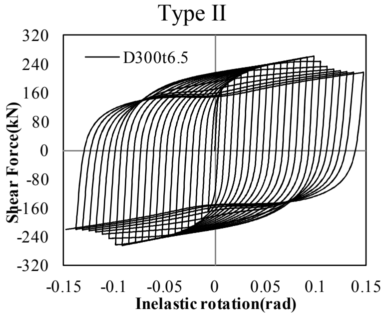
Fig. 8 Deformed shape and von Mises stress distribution



Type I



Type II



Type III

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

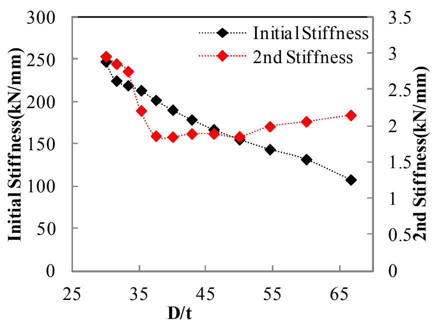


Fig. 10 Effect of D/t ratio on initial and second stiffness

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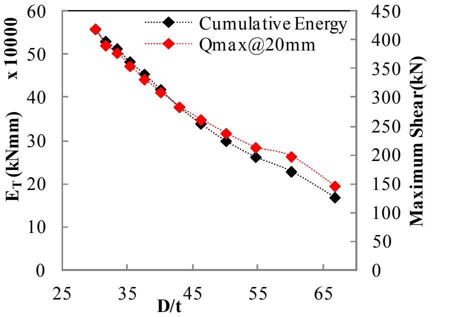

Fig. 11 Effect of D/t ratio on cumulative energy and shear capacity

B. Effect of Stiffness

The effect of stiffener in CSPD is also presented in this study. Different stiffener arrangement is introduced and the result is evaluated. The stiffener is installed in one face of circular diaphragm plate parallel to loading direction (horizontally), perpendicular to loading direction (vertically), both horizontal and vertical stiffener and stiffener with an X-shape on D300t8.5 analysis specimen. The stiffener plate has 5mm thick and 20mm width. The deformation shape with von Mises stress contour and hysteresis loops is presented in Figs. 12 and 13 respectively. The von Mises stress is evenly distributed for horizontal and X-shaped stiffeners compared the other two. Out-of-plane buckling is reduced in case vertical stiffener. Looking at the hysteresis loops, vertical and cross stiffener shows stable relative horizontal and X-shaped. In order to evaluate the maximum load resisting capacity monotonic loading analysis was conducted. The comparison of different specimens with stiffeners and without stiffeners for monotonic loading analysis is shown in Fig. 14.

The load increment ratio calculated from hysteresis loops of analysis model presented in Fig. 13 using (3) below:

$$\zeta = \frac{Q_{\max_i}}{Q_y} \tag{3}$$

where ζ 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. 15. As shown in the Fig. 15, the increment ratio increases in constant rate for specimen, no stiffened, vertical and cross shaped stiffened specimens. Horizontal and X-shaped stiffened specimen start decrease after peak point 30 and the rate of decrease of X-shaped stiffened specimen high.

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. 16. The energy absorption capacity and shear capacity of circular hollow section without a thin circular diaphragm is presented in Fig. 17 with variable diameter. As shown in the figure both cumulative energy and maximum shear resisting capacity decreases with an increase D/t ratio. The effect of CSR on cumulative energy absorption and shear capacity on CSPD is 5.12%, and 6.73% respectively.

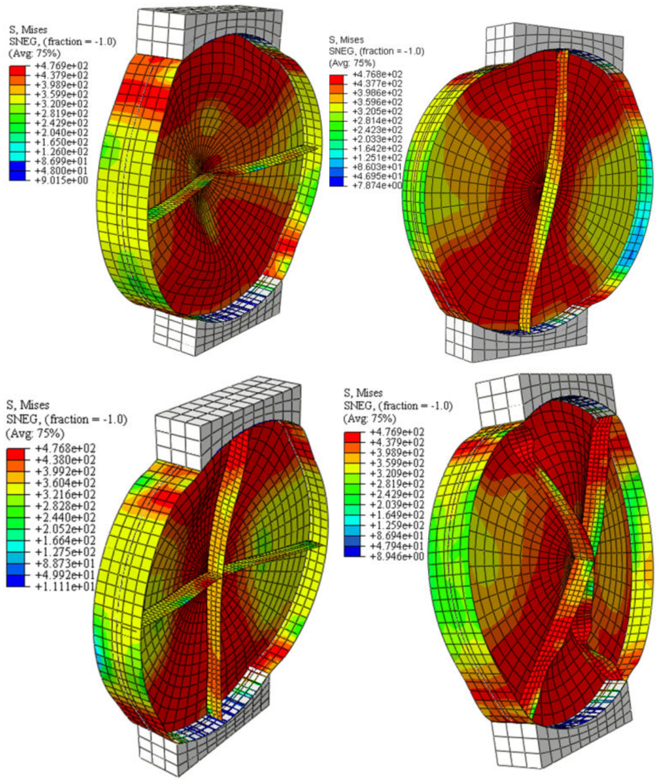

Fig. 12 Effect of stiffener on von Mises stress contour and deformed shape

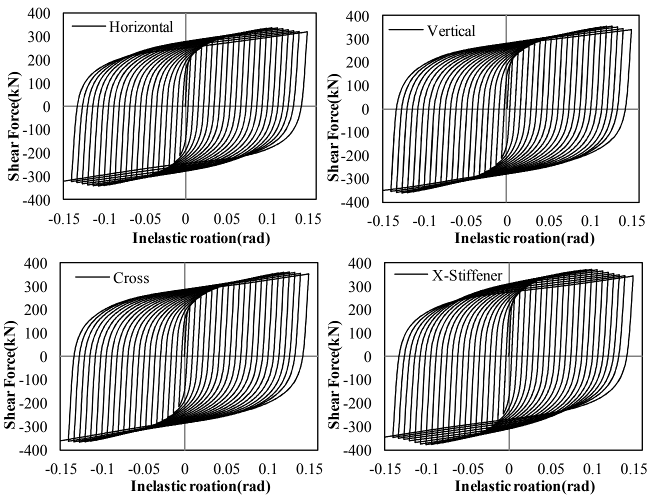

Fig. 13 Effect of stiffener on hysteretic loops

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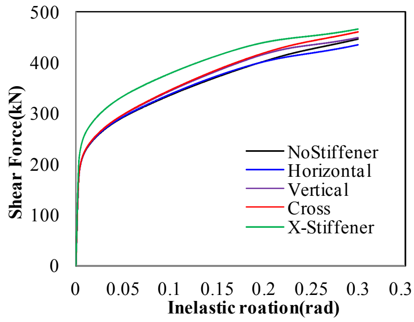

Fig. 14 Effect of stiffener on resisting capacity

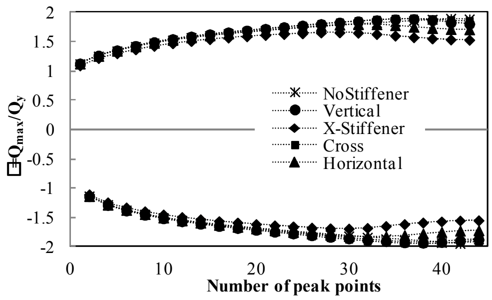

Fig. 15 Relationship between load increment ratio to numbers pick points

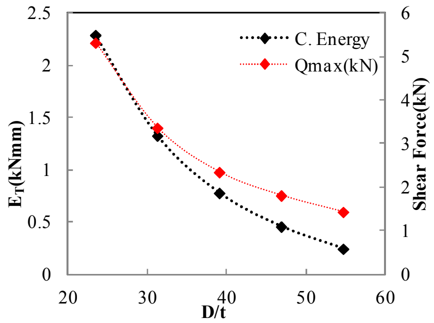

Fig. 16 Cumulative energy and shear capacity of CSR

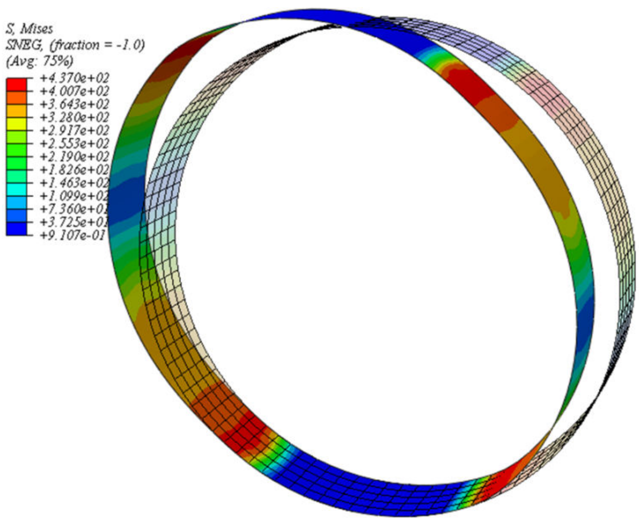

Fig. 17 Deformed shape and von Mises stress distribution of CSR

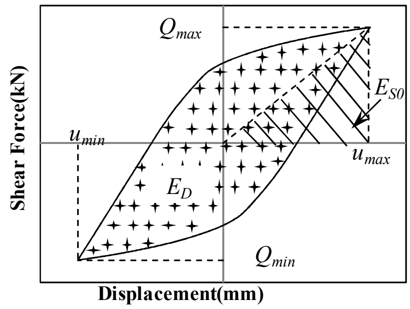

Fig. 18 Effective stiffness and energy dissipated in a cycle [7]

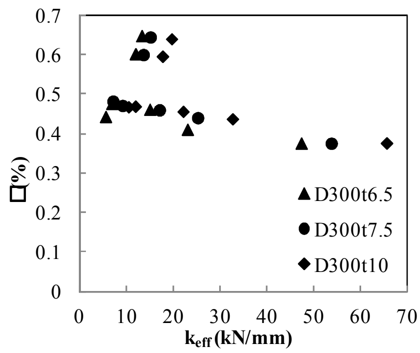

Fig. 19 Relationship of effective damping ratio and equivalent stiffness

D. Equivalent Device Stiffness and Damping

As stated in [8] it is accepted that energy dissipated in cyclic straining of metals is rate-independent. For practical use it is sometimes preferable to express the device properties in an equivalent viscous system. The equivalent stiffness k_{eff} defined from Fig. 18 as,

$$k_{eff} = \frac{|Q_{\max}| - |Q_{\min}|}{|u_{\max}| - |u_{\min}|} \tag{4}$$

The damping ratio for the equivalent system, ζ_{eq} can be obtained by equating the measured energy dissipated per cycle (*ED*) in the experiment to that of a viscously damped oscillator [14],

$$\xi_{eq} = \frac{1}{4\pi}\frac{E_D}{E_{SO}} \tag{5}$$

where E_{S0} is the energy stored in an elastic spring with a stiffness k_{eff} and displacement u_{max}.

Fig. 19 shows the relationship between effective damping ratio and equivalent stiffness at different loading cycle. Each point represents a feasible stiffness and equivalent damping ratio of the proposed device. Generally, after the device enters into the plastic range the effective stiffness decreases as the device undergoes larger displacement.

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V. CONCLUSION

This study evaluates the hysteresis performance of circular shear panel damper both stiffened and without stiffener. Different parameters were considered. It is found that, D/t ratio has significant and sensitive effect on the hysteretic behavior, deformation mode, maximum shear resisting capacity and hence cumulative energy. When the D/t decreases the shear resisting capacity increases and the hysteretic behavior becomes stable.

All types of stiffeners has no significant effect on CSPD in both plastic deformation and hysteretic behavior. Rather because of an early yielding of stiffener the hysteretic behavior is not stable compared to CSPD without stiffener.

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