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Analytical Evaluation on Structural Performance and Optimum Section of CHS Damper

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Abstract**—**This study aims to evaluate the effective size, section and structural characteristics of circular hollow steel (CHS) damper. CHS damper is among steel dampers which are used widely for seismic energy dissipation because they are easy to install, maintain and are inexpensive. CHS damper dissipates seismic energy through metallic deformation due to the geometrical elasticity of circular shape and fatigue resistance around connection part. After calculating the effective size, which is found to be height to diameter ratio of $\sqrt{3}$, nonlinear FE analyses were carried out to evaluate the structural characteristics and effective section (diameter-to-ratio).

Keywords**—**Circular hollow steel damper, structural characteristics, effective size, effective section, large deformation, FE analysis.

I. Introduction

DAMAGE control design concept for civil engineering structures have been widespread to mitigate hazards caused by earthquake since 1995, Kobe, Japan earthquake disaster [1]. Over the same period, after the 1995 Hyogo-ken Nanbu earthquake, structural control has paid much attention to seismic design, with the premise that such control can improve ultimate resisting capacity of structures and reduce damage during earthquake [2]. There are a number of methods to improve the resisting capacity as well as to reduce the damages during earthquakes. Steel damper is among these methods which is a type of passive control device that uses the hysteresis of the material as the source of energy dissipation. Circular hollow steel damper is a type of passive control device that dissipates seismic energy through inelastic deformation or hysteresis material. The advantage of using CHS-damper over other steel dampers such as shear panel damper is CHS damper in the practical situation can resist loads in all direction as the action of force during earthquake is multi-dimensional because of its circular shape [3], [4].

In this study, the finite element analysis was conducted for grasping the structural characteristics and to identify the effective section (diameter-to-thickness ratio of hollow section steel damper after calculating the effective size. To confirm the validity of the analysis method, the comparison between test result and analysis result was undertaken. In order to identify the effective section, parametric studies taking diameter -to-thickness (d/t) ratio as main parameter is conducted and based on the parametric analysis result, the efficient diameter to thickness ratio is recommended in terms of PEEQ index.

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II. Calculation of Effective Size

Before starting the experimental and FE simulation on CHS damper, it important to identify the effective size at which the developed stresses, both bending and shear stresses, are resisted equivalently. Thus, using simple engineering mechanics, the effective size is derived in terms aspect ratio (height to diameter ratio). Theoretically the whole system of CHS damper is considered as a fixed ended beam as shown in Fig. 1. The corresponding bending stress and shear stress distribution on the cross-section is shown in Figs. 2 (a) and (b) respectively.

By taking infinitesimal length, as shown in Fig. 3, the bending stress is given by:

$$\sigma_\theta = \frac{M}{I} \quad (1)$$

where: M: bending moment, y: the distance of the area from the neutral axis and is given by y=rsinθ, I: second moment area given by $I=\pi r^3 t$.

Substituting y and I in (1), the bending stress will be $\sigma_\theta = \frac{M}{\pi r^2 t}\sin\theta$; and it is maximum for $\theta = \frac{\pi}{2}$,

$$\sigma_{\max} = \frac{M}{\pi r^2 t} \quad (2)$$

Whereas the shear stress (τ) is defined as: $\tau_\theta = \frac{Qr^2}{I_x}\cos\theta$ substituting for $I = \pi r^3 t$ and $Q = \frac{M}{h}$, then the shear stress will be expressed as:

$$\tau_\theta = \frac{M}{\pi r t h}\cos\theta \quad (3)$$

Shear stress is maximum for θ = 0°, at which the cosθ = 1, then

$$\tau_{\max} = \frac{M}{\pi r t h} \quad (4)$$

The uni-axial and shear yield stresses for the von Mises criterion are related by [5]:

$$\sigma_y = \sqrt{3}\tau_y \quad (5)$$

Substituting (2) and (4) to (5) we can have:

$$\frac{h}{r}=\frac{H}{D}=\sqrt{3} \qquad (6)$$

This size of CHS damper section is considered as an effective size where both bending and shear stresses resisted and it also satisfies the von Mise's yield stress criteria. The failure mode of CHS damper is different depending on the height to diameter ratio. Specimen having H/D greater than $\sqrt{3}$ the failure is bending failure and the failure for specimen having H/D less than $\sqrt{3}$ is shear failure [6]. The detail of specimen of effective size is presented in Fig. 4. Knowing the effective size, non-linear FE analysis was conducted to identify the optimum section of circular hollow section steel damper.

III. Nonlinear FE Analysis

A. Material Modeling

Circular hollow steel damper was discretized using a three dimensional finite element analysis model called ABAQUS package to evaluate the structural performance of CHS damper (ABAQUS 6.10) [7]. 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 element through mesh generation by Python script is found to be more efficient in modeling CHS damper with linear interpolation and reduced integration are used, as shown in Fig. 5. 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. Each ends of the components are created a more refined mesh, as shown in Fig. 5. as that is where most stresses are concentrated and is the area exposed direct compression and tension forces.

B. Loading Condition

All the translational and rotational displacement components are fixed at lower end plate. A cyclic load was given at upper end plate in X-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. 6.

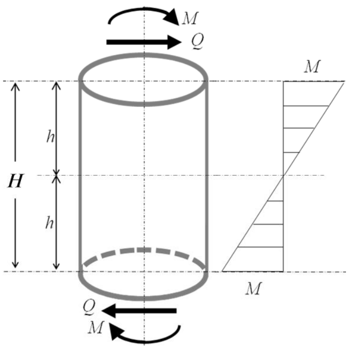
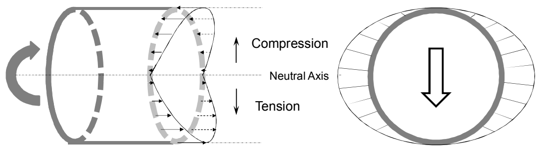


Fig. 1 Loading condition



(a)Bending Stress Distribution (b)Shear Stress Distribution

Fig. 2 Stress distribution on CHS Damper

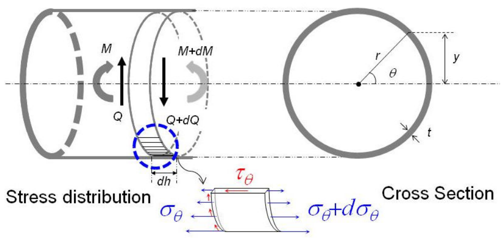


Fig. 3 Stress distribution on the infinitesimal length

IV. Experimental Study

In order to verify the analysis model a quasi-static loading test was conducted. The test set-up and general equipment system is shown in Fig. 7 to test the specimen detailed in Fig. 4. In this system, to avoid rotation angle on the top of specimen pantograph was installed and counter weight installed using a principle of a pair of scale was arranged to protect axial force application to experiment specimen. Displacement meters for measuring deformation of circular hollow steel dampers were installed at the top end plate and the bottom end plate of the experiment specimen. Average value of the right and left side displacement devices was evaluated as displacement value of the experiment specimen. In addition, horizontal force on the experiment specimen was measured by installing load cell on the actuator. Experimentally the both hysteresis behavior up to final failure is measured through cyclic loading. The load is applied by controlling the displacement. The displacement protocol used for experiment is the same as the protocol used in the analysis model.

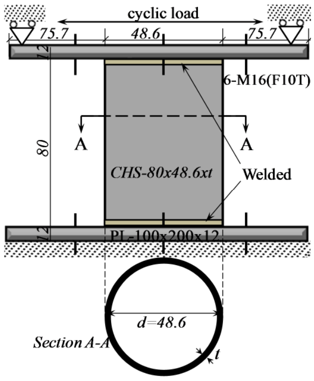


Fig. 4 Specimen detail and boundary conditions

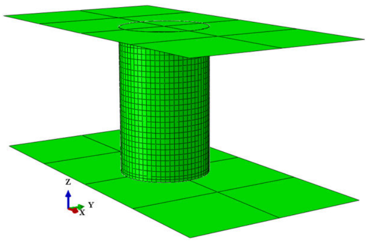


Fig. 5 3D analysis model

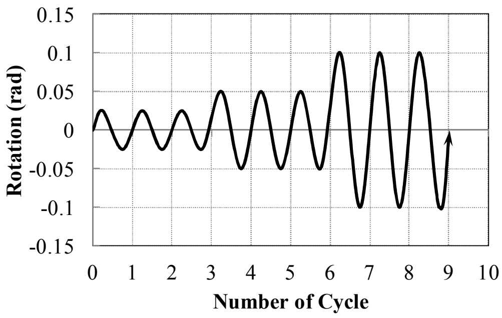


Fig. 6 Loading protocol

V. Results

A. Shear Force and Shear Rotation Relationship

Shear force and shear rotation angle of analysis and quasi-static loading text result is compared as shown in Fig. 8.

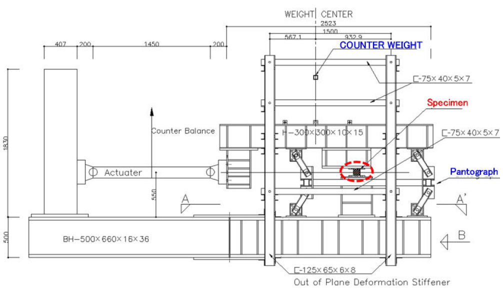


Fig. 7 Shear force-Inelastic rotation relationship

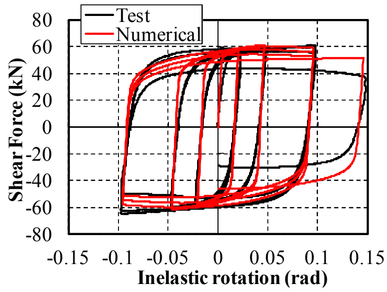


Fig. 8 Comparison of shear force-inelastic rotation relationship

Looking at the hysteresis loop of Fig. 8, there is no apparent difference between the quasi static test result and FE simulation results. Which shows that FEM analyses accurately evaluates the failure mode, hysteresis characteristics and the performance of CHS damper. In the plotted graph, the black solid line represents experimental result and the red line shows the analysis result. The numerical result has larger strength in the first five cycles relative to experimental result in hysteresis loop.

B. Parametrical Study

To evaluate the optimum section of circular hollow section steel damper the effect of section considering diameter-to-thickness (D/t) ratio is studied analytically. The optimum section identified using PEEQ index. The equivalent plastic strain (peeq) is a parameter related to ductile crack initiation and the plastic deformation capacity [8]. To investigate the local effects of D/t, the peeq was measured location shown in Fig. 9. The peeq index is defined as in below.

PEEQ Index*:* is given by the ratio of the plastic equivalent strain to the yield strain.

$$PEEQIndex = \frac{\varepsilon_e^p}{\varepsilon_y} \tag{7}$$

where ε_e^p:is the equivalent plastic strain and ε_y: yield strain which is given by the ratio of yield strength to young's modulus $(\sigma_y/E)=0.002$. The equivalent plastic strain was measured around half circumference at middle of the specimen at each node starting from the direction of loading as shown in the section in Fig. 9. The calculated maximum equivalent plastic strain index (PEEQ Index) around the circumference with the corresponding diameter to thickness ratio is presented in Fig. 10. Looking at the figure, as the d/t increase up to about D/t=10.8 the PEEQ Index decreases with small rate and for D/t =10-20 the PEEQ index keeps constant. For d/t ratio greater than 20, the PEEQ Index increases dramatically. The PEEQ index measured in longitudinal direction is also presented in Fig. 12. As shown in Fig. 12, the peeq index for D/t ratio of less than 20 has two critical points. The maximum equivalent plastic strain index calculated around the circumference and in longitudinal is plotted with respect to D/t ratio is summarized in a curve with an S-shape curve shown in Figs. 11 and 13 which is grasped from Figs. 10 and 12 respectively. As shown in these Figs. 11 and 13, region at which PEEQ index is the minimum (d/t=10-20) is the region of optimum section of CHS-damper.

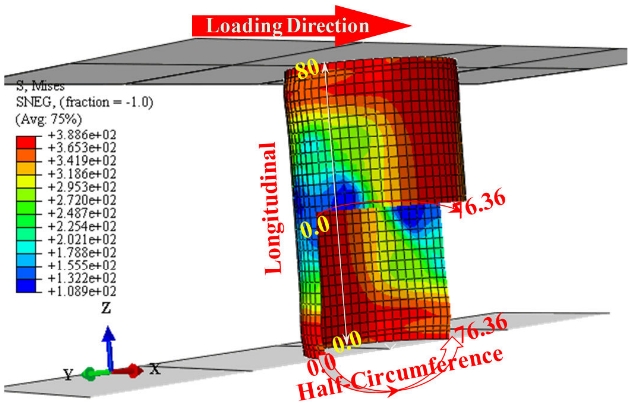


Fig. 9 PEEQ measurement location

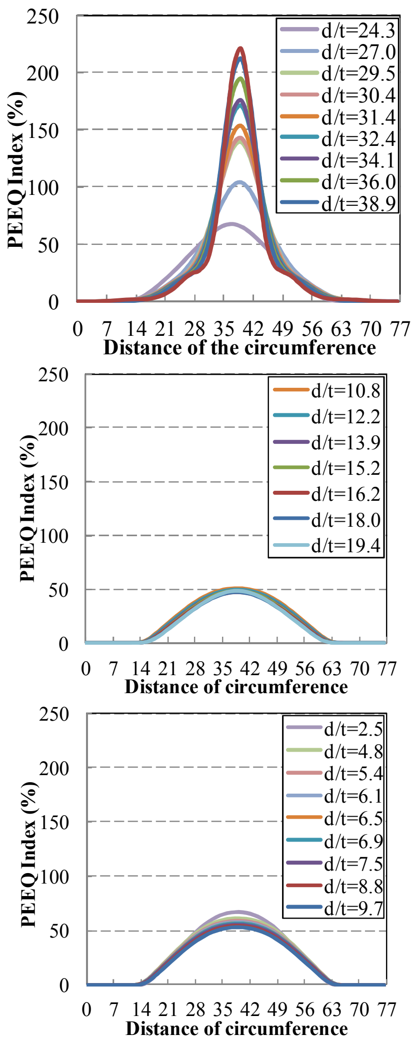


Fig. 10 Equivalent plastic strain index measured in half circumference

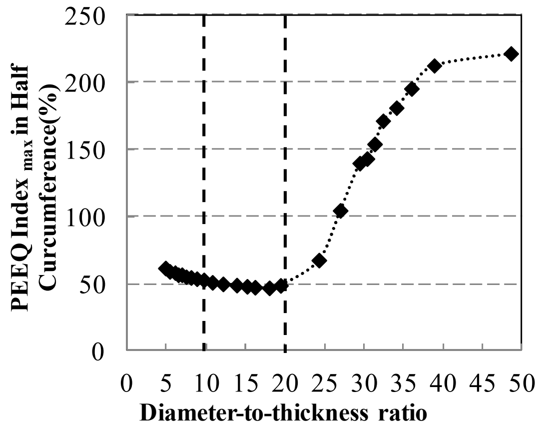


Fig. 11 Circumference PEEQ Index- d/t relationship

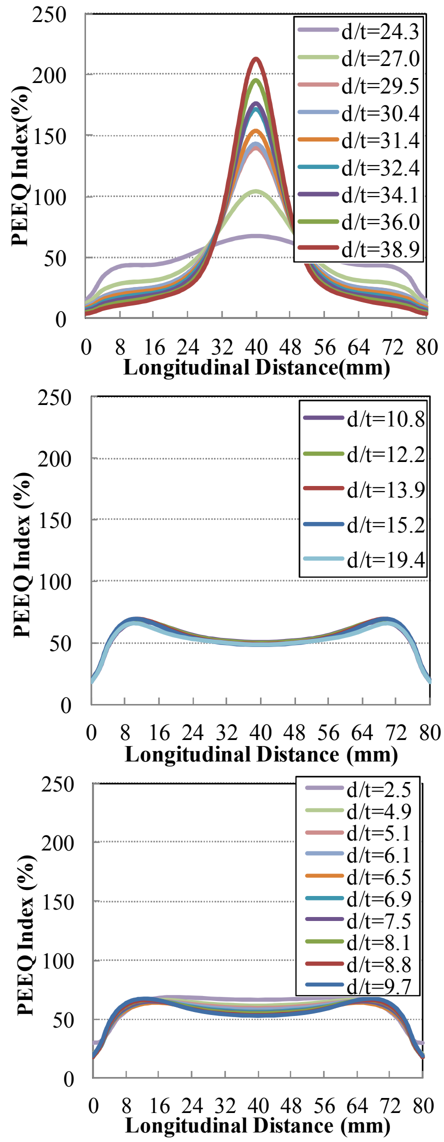


Fig. 12 Equivalent plastic strain measured longitudinally

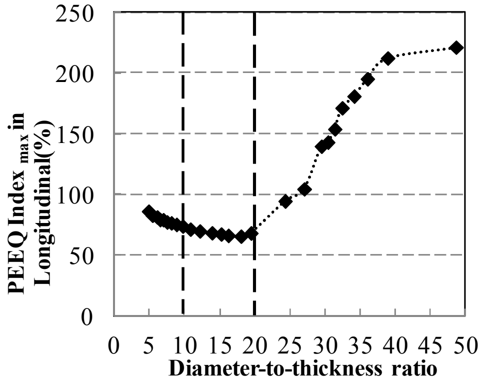


Fig. 13 Longitudinal PEEQ Index- d/t relationship

VI. Conclusion

After calculation of effective size, FE simulation was conducted and of course the FE simulation was also verified through experiment by comparing the shear force and shear rotation relationship. From comparison it is noted that there is no apparent difference between the two results obtained which shows the accuracy of FE simulation conducted. For analysis specimen failure index as well as PEEQ index was calculated. The effect of diameter-to-thickness ratio in CHS damper was studied and the optimum section is identified in terms of PEEQ index. The optimum section is found to be diameter-to-thickness ratio of approximately 10-20 which shows the region with low PEEQ Index.

Acknowledgment

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