Hysteretical Behavior of Steel Slit Dampers Subject to Geometric Changes

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Abstract. In the last decades several alternatives to obtain buildings that present a more efficient behavior to seismic events have been developed, one of these alternatives is the implementation of passive energy dissipation systems that modify the dynamic characteristics of the structure thus controlling its deformation and subsequent damage. Particularly, steel slit dampers are an inexpensive alternative and they have proved reliable and easy to install and maintain. This paper evaluates the hysteretic behavior of metallic dampers subject to cyclic load. The amount of energy that a steel slit damper can absorb is determined numerically by means of a finite element model and a comparative analysis of sensitivity to changes in shape and distribution of holes, thickness and width-height ratio of the plate is presented.

Keywords: Yield damper, Numerical analysis, cyclic load.

1 Introduction

Traditional design methodologies for earthquake resistant buildings attempt to protect human lives, but they allow that the structures achieve damage levels after a larger earthquake that could result in repairs financially unfeasible. Because of this, in last decades, the conventional building design philosophy has been changing from a philosophy based on physical resistance to one where the responsibility of the energy dissipation is put on additional seismic devices. In that sense, seismic protection systems have been developed and incorporated into structures to minimize or reduce damage induced by earthquakes. Within these systems, passive dissipation devices have proven to be an effective and economical way to reduce the structural response [1]. They absorb energy induced by earthquake by different mechanisms, such as metal yielding, friction, fluids passing through holes, and viscous elastic deformation of solid [2].

In the past 25 years, several innovative hysteretic steel dampers have been proposed and tested, such as TADAS device, ADAS device, yielding shear panel, rhombic ADAS, dual-function, slit damper, buckling restrained brace and circular plate damper [3]. Figure 1 shows several shapes of hysteretic steel dampers based on plates, which can work by the yielding of the material produced by either flexure or shear movements. It is important to recall that it is necessary to define appropriately the hysteretic model describing the cyclic behavior of the devices to guarantee a correct earthquake-resistant design of buildings equipped with such as dampers.

Concerning steel slit dampers, it is necessary further studies to determine the effect of the geometrical shapes of steel dampers in the get of good and stable in energy dissipation capacity. The scope of this paper covers details of the Finite Element modelling technique using ANSYS and a parametric study of the size and distribution of the slits and the relation heigth-width of the plate.

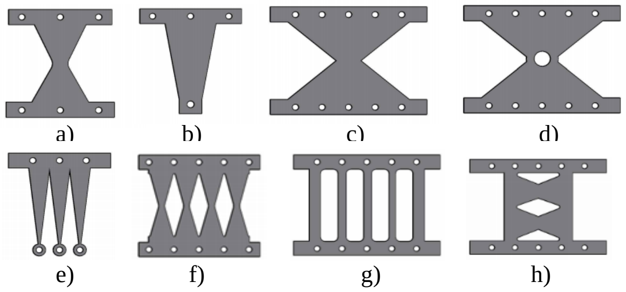

a) b) c) d)
e) f) g) h)

Figure 1. Types of steel dampers a) ADAS b) TADAS c) X-Shaped d) Single round-hole e) Comb-Teeth f) Parabolic g) Slit damper h) Double X-Shaped

2 Finite Element Modeling of Steel Slit Damper

2.1 Material Modeling

An appropriate material model is a prerequisite to obtain accurate predictions from a finite element model. Stress-strain response of ordinary steel shows three defined regions: i) an initial elastic response; ii) a middle region with strain hardening up to the ultimate stress and iii) strain softening before failure. For the steel slit dampers, Chan and Albermani [4] used an elastic perfectly plastic model, which was calibrated with information from an experimental test of the damper under monotonic load. The same model was implemented by Ghabraie et al. [5] to calculate the value of strain energy of the damper subjected to a single symmetric load cycle, they reported that the model used was not capable of predicting device failure. Oh et al. [6] used a trilinear model proposed by Benavent et al. [7] where the slope of the second line is 4% of the modulus of elasticity and the slope of the third line is 0.8% of the modulus of elasticity, for modeling a flexural yielding steel slit damper in a beam-column connection. Hossain et al. [8] used a bilinear kinematic hardening model in which the slope of the second line is 1% of the modulus of elasticity for the finite element modeling of Yielding Shear Panel Devices under monotonic and cyclic loading conditions. Karavalisis et al. [9] used the Bouc–Wen model modified to capture the combined kinematic and isotropic hardening seen in the hysteresis of steel devices. Hedayat [10] used a trilinear model with isotropic hardening for monotonic loading and kinematic hardening for the cyclic loading case and Amiri et al. [11] used a bilinear model with kinematic hardening to simulate the behavior of a block slit damper under cyclic loading. Although the discussion on material models is still open, according to the previous review, it is appropriate to say that an isotropic hardening model may be used to simulate the material behavior only for monotonic loading, whilst cyclic behavior would require a kinematic hardening model as the yield surface can translate in the direction of loading.

To study the influence of the shape and distribution of the slits in the energy dissipation capacity of the damper, the Ghabraie's conditions were replicated for devices subjected to a single symmetric loading cycle. The bilinear model shown in figure 2 was used, which is similar to that described by Hossain [8]. Concerning the material properties, Chan et. al. [4] and Ghabraie [5] reported two standard coupons test from the web of the section that gave an average tensile yield stress of 316.5 N/mm^2 and a modulus of elasticity of 206.1 kN/mm^2.

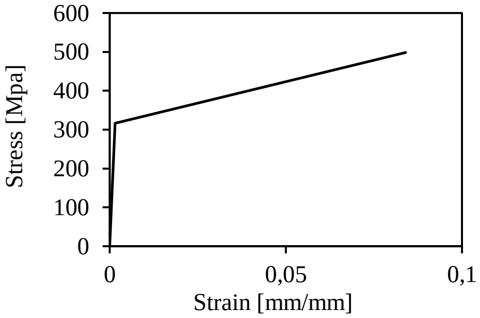


Figure 2. Material properties

2.2 Element type and analysis settings

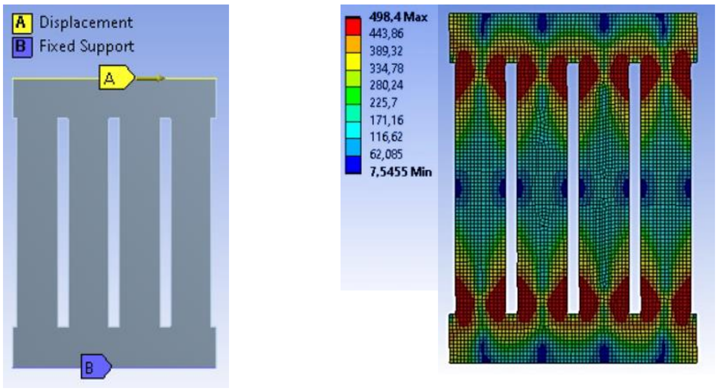
ANSYS Workbench program was used for determining the hysteretic response of steel slits dampers under cyclic displacements. Using the Static Structural tool, a nonlinear 'STATIC' analysis to simulate the force-displacement response of the slit damper was made. For solving the global system of simultaneous linear equations generated by the finite element procedure, the program has techniques of direct elimination or iterative methods. The direct solver available is the Sparse Direct Solver that makes use of the fact that the finite element matrices are normally sparsely populated. This sparsity allows the system of simultaneous equations to be solved efficiently by minimizing the operation counts. The iterative solvers are based on the conjugate gradient method and include the Jacobi Conjugate Gradient (JCG) which is suitable for well-conditioned problems, the Preconditioned Conjugate Gradient (PCG) which is efficient and reliable for all types of analyses including the ill-conditioned beam/shell structural analysis and the Incomplete Cholesky Conjugate Gradient (ICCG) is more robust than the JCG solver for handling ill-conditioned matrices [12]. The direct method was used, which is the default. For convergence of nonlinear problem, the program uses Newton Raphson and line search option was activated because can further improve the performance of the solution technique.

To study the cyclic behavior the thermal effects were no considered, general purpose shell element 'SHELL181' available in ANSYS [13] was used in the current research to model the damper. 'SHELL181' is a 3D four-noded full integration quadrilateral shell element with six degrees of freedom at each node. About the mesh, a suitable one must consider the type of structure and the corresponding analysis involved, finer mesh generally provides better predictions but require higher computational time. In this work, the maximum size for each element was 1,5mm because the displacements that were applied caused great strains and stress.

The displacement cycle is made up of three movements applied to the top of the plate in X direction, one of 10 mm to the right, a second movement of 20 mm to the left and finally another of 10 mm to the right to return to its original position. Cyclic loading was applied at top end of the specimen and bottom zone was fixed in all direction as indicated the figure 3a.

2.3 Load-deformation response under cyclic load

First, the standard V84 device proposed by Ghabraie et al. was modeled to compare with the results of the model proposed in ANSYS. The dimensions of the specimen are width W_d = 100mm, overall height H = 162mm and thickness t = 8mm. But as explained in the reference, the considered design area has height H_d = 139mm.



(a) (b)

Figure 3. Devise V84 a) Boundary conditions b) Results stress distribution V84

The stress distribution on the plate is shown in figure 3b. he stress distribution on the plate is shown in figure 3b. For cyclic load, the energy dissipated is the area under the hysteresis curve, in this case, because the loading sequence consists of a full cycle, the total plastic dissipation will be equal to the total strain energy. In Ghabraie et al. [5], an initial energy dissipation capacity of 1124 J is reported. In this work, with the described modeling methodology, 1103 J were obtained. The discrepancy is acceptable since there were no data on the plastic behavior of the material.

3 Shape influence

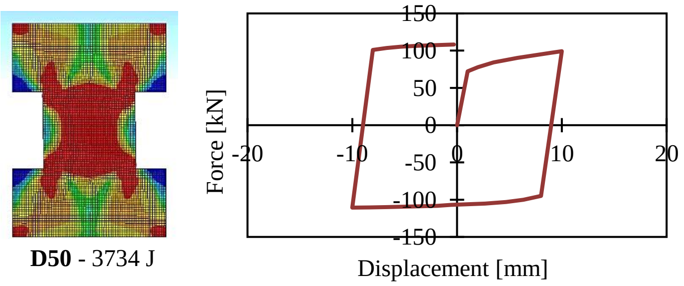
To identify behavior patterns related to the material distribution of the damper, a group of 120 devices with one to four rectangular slits were studied to make comparisons, all devices present the same amount of material. The study was made varying two parameters of shape, table 1 shows the variations made to the width and height. The thickness is 8mm for all specimens.

Table 1. Parameters of the study (w_s and h_s)

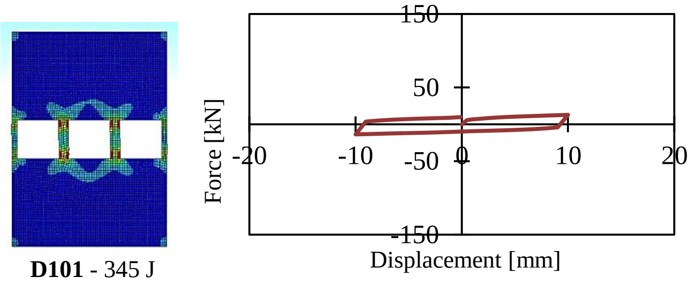
One slit		**Two slits**		**Three slits**		**Four slits**	
Width [mm]	**Heigth [mm]**	**Width [mm]**	**Heigth [mm]**	**Width [mm]**	**Heigth [mm]**	**Width [mm]**	**Heigth [mm]**
20	100	10	100	7	100	5	100
22	90	14	70	9	75	7	71
25	80	17	60	15	45	11	45
29	70	20	50	27	25	20	25
33	60	25	40	44	15	33	15
40	50	50	20				
50	40						
67	30						

In the first place, devices with vertical slits were studied, the value of the width and height of the holes was changed as can be seen in Table 1. The width was increased as far as possible while respecting the width restrictions of the plate and amount of material. In this first stage, it was found that in terms of the height over width ratio of the slits (h_s / w_s), very small values reduce the dissipation capacity because the portion of material between the holes becomes thin and causes stress concentrations. In general, an increase in the h_s/w_s ratio increases the maximum force, however, this increase only occurs in a certain range. Outside this range, the force begins to decrease.

After that, the same slits were located in other parts of the plate and devices with wider slits were also modeled. The amounts of energy found in this study ranges from 345 J to 3734 J. Remembering that all the devices studied had the same amount of material, it is important to review the possible causes and, to expose the importance of the distribution of the holes on the web of the profile, two of the modeling results are shown in Figure 4. The first is the device, which within those studied, achieved more capacity (3734 J), the specimen has two slits of 20x50mm; the second is the one with less capacity (345 J), has three slits of 25x25mm. These results are because it is very important to reduce the stress concentration in the damper and clearly the second geometry does not allow a correct distribution of stresses throughout the material.



D50 - 3734 J



D101 - 345 J

Figure 4. Higher and lower strain energy, device D50 and D101, respectively

Another aspect observed is that, from the standpoint of energy absorption, dampers with two rows of blades or with slits located at different heights, have more capacity than the single-row ones. It is also notable that the D50 device, which was the one that dissipated the most energy in this study for a single displacement cycle, exceeds the amount of energy of the device optimized by means of the BESO algorithm in the work of Ghabraie et al. [5] which achieved 2203 J for the same displacement cycle. This indicates that other optimization techniques or other parameters can be used to improve the design results of these devices. However, it cannot be guaranteed that the D50 will perform better for more charge cycles, it is something that must be studied with experimental test or advanced numerical models.

Because the loading cycle is symmetric, that is, the same displacement is applied to the right and left, it was possible to identify lines of symmetry. It is necessary to mention that if the load is not symmetric, the amount of strain energy for a certain geometry will not coincide with the amount of its reflected versions with respect to the vertical and horizontal axes, all the devices will have different capacities.

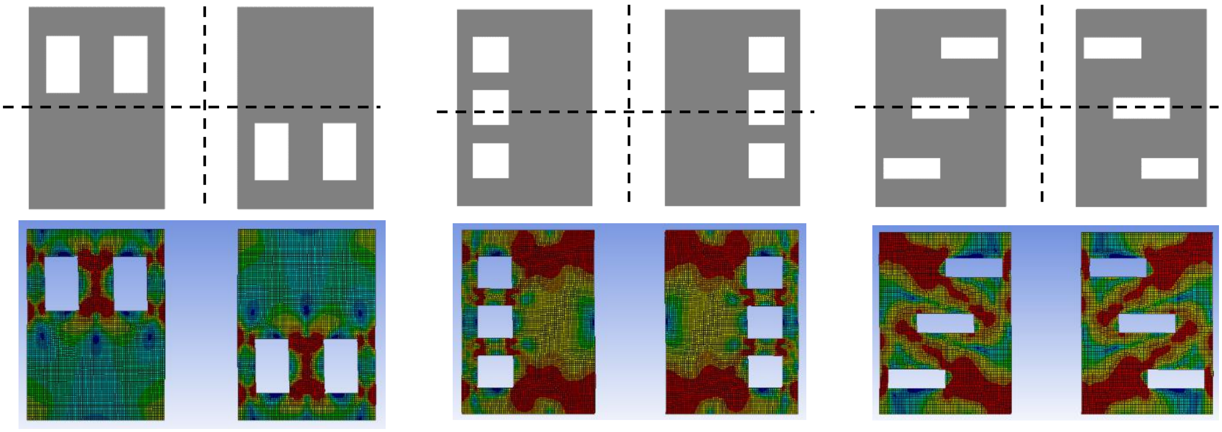

a) b) c)

Figure 5. Axes of symmetry

In addition, the influence of the width and height dimensions of the plate was studied for the D50 device, which was the one that dissipated the most energy in this study. The new height (H_d) x width (W_d) dimensions were as follows: 70x199, 80x174, 100x139, 149x93, 202x69 mm. In this opportunity, the same amount of material was also kept. The results show that the wider plates allow a better stress distribution than the higher ones, so the amounts of strain energy of said plates are considerably higher as seen in the figure 6. However, due to the nonlinear nature of the problem, the loading sequence will affect the mechanical responses, so these results are partial since only one displacement cycle was applied. If the behavior of each damper is studied under a full displacement protocol with several cycles, the results may change since some devices will resist more loading cycles than others, which will be reflected in a greater or lesser amount of accumulated strain energy.

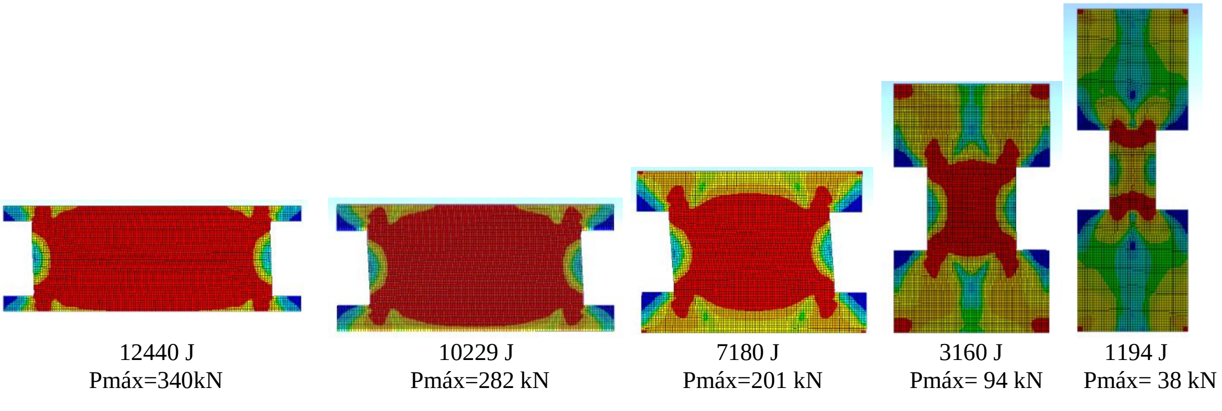
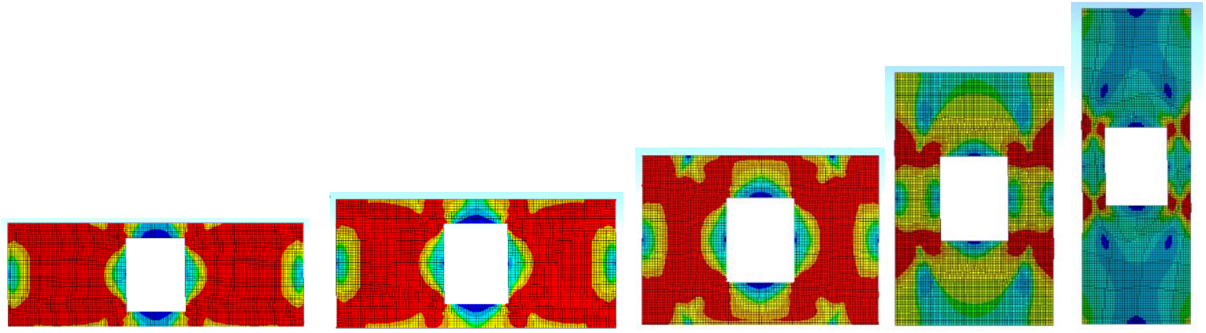


Figure 6. Height-width relation for device D50

For another design with internal slits, something similar happens as show Figure 7. The wider devices reach higher forces. It was found that when the plate is wide, the edges in contact with the fixed support and the load are longer, this influences the capabilities of the device since the reaction force increases. That is, when the contact surface between the boundary conditions and the damper is large, the device experiences greater and more uniform stresses.

It is possible that exists a limit to the value of the relationship between width and height. For very high plates, the amount of energy is reduced because the device can resist large displacements but develops very low forces while, for very wide devices, large forces develop but short displacements, so there is an optimal width (W_d)-height (H_d) ratio that favors the energy dissipation capacity maintaining the stable hysterical behavior of the damper, but it is necessary to study this behavior when there are more load cycles or under monotonic load to know the maximum displacement to each damper could be subjected.



10879 J
Pmáx=302 kN

8553 J
Pmáx= 241 kN

5418 J
Pmáx= 159 kN

1900 J
Pmáx=58 kN

602 J
Pmáx= 19 kN

Figure 7. Height-width relation for another device

4 Conclusions

For rectangular slits located conventionally (vertically), it is convenient that the height-to-width (h_s/w_s) ratio is large. Very wide holes produce stress concentration which results in low capacity; however, it was observed that for very thin holes the capacity also decreased compared to those slits with intermediate h_s/w_s ratio. When studying the behavior of dissipators in a numerical way under cyclical and symmetrical load, it is found that the stress is distributed in a similar way for a geometry and its versions reflected horizontally and vertically. By increasing the width of the damper, the forces are increased, however, these forces are reached with little displacement which could affect the behavior for subsequent load cycles.

As can be seen for the plates that dissipated the highest energy values, almost all the material has reached the ultimate stress, then to determine if the hysterical behavior of the damper is stable it is important to study its behavior in subsequent cycles by doing experimental tests or at least an advanced numerical model.

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