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Research paper

Topology optimization of steel slotted dampers with the hybrid cellular automata technique

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ABSTRACT

Cellular automata is a computational technique that has proven valuable for solving engineering problems. In the field of structural optimization, it has been applied to find the optimal topology of a structure, given the similarities between the problem characteristics and the computational representation. This paper proposes a cellular automata-based methodology for the topology optimization of steel slotted dampers. A multi-objective approach is formulated to maximize the energy dissipation capacity and minimize the damper's mass. A single-cycle displacement protocol is utilized to determine energy dissipation capacity in Ansys. The results demonstrate that the proposed algorithm improves the optimal shape obtained from a configuration with vertical slots more efficiently than other two algorithms in the literature. The energy dissipation capacity was increased by 3.5 times while using only fourteen iterations to converge. By testing several initial slot configurations, the CA-based method proved to be less dependent on the initial decision. Finally, the effects of using a one-cycle displacement protocol, symmetry considerations, and the height/width ratio are also discussed.

1. Introduction

Today, computational intelligence (CI) techniques are widely used to solve everyday human problems. In civil engineering, CI has demonstrated its potential in a variety of problems, as evidenced by Demertzis et al. [1]. Despite that, the scientific community has yet to reach a consensus on defining CI. In this work, it is adopted Engelbrecht's definition [2], which relates CI to the development and use of computational paradigms that foster intelligence behavior to solve complex problems. From this perspective, Sumathi and Pannerselvam [3] classify CI techniques into computational paradigms such as artificial neural networks, fuzzy logic, evolutionary computation, swarm intelligence, and others. One of these paradigms is the cellular automata, a type of evolutionary computing. Cellular automata are mathematical idealizations of natural systems with discrete nature, so they may be viewed as simple construction parallel processing computers [4].

CI techniques have been applied to the seismic protection of structures to tackle different issues. Vaidyanathan [5] evaluated a multilayer perceptron neural network to predict the peak displacement, the effective period, and the effective damping of a three-story building with viscoelastic dampers. Abdulateef and Hejazi [6] used fuzzy logic to offer robustness in the vibration control of structures with magnetorheological dampers, addressing uncertainties associated with the loads and structural properties. Metaheuristics have been employed to optimize the configuration of structures equipped with seismic protection devices, as shown in Refs. [7–10]. Additionally, it is possible to determine the optimal shape of devices, such as Steel Slotted dampers [11–13]. The amount of energy that a SSP damper can dissip is related to the shape, size, number, and distribution of slots, as well as the thickness and dimensions of the plate. This complexity hinders the practical selection of the optimal shape for the plate, but there is no consensus on how is the best approach for solving the problem. One critical issue corresponds to the computational cost of calculating the energy dissipation capacity from the non-linear finite element analysis. To the authors' best knowledge, cellular automata have not been explored for problems involving SSP dampers.

More research is needed on applying cellular automata in civil engineering to understanding their capabilities. Qiao et al. [14] used a 3D cellular automata in the prediction of the effects of corrosion in reinforced concrete structures. Schadschneider [15] used cellular automata to model the traffic on a highway, considering that a maximum of one car can fill each cell. Su et al. [16] studied the problem

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of a piping breach in an earth-rock dam based on a representation of cellular automata and a transformation rule during the failure process of the soil dam. Ozelim and Cavalcante [17] employed a tridimensional array of cellular automata for modeling the pore network in soils. Feng et al. [18] modeled the surface runoff in an urban environment during rainfall, considering both the spatial and temporal domains. Araghi and Stouff [19] integrated cellular automata to define the layout of a set of residential buildings, considering the cells as specific installations. An exciting application of cellular automata is the topology optimization of structures due to the straightforward link between the problem representation and automata arrays. Tovar [20] used cellular automata combined with finite element modeling to obtain the optimal topology for 2D structures. From this experience, cellular automata are a feasible technique for determining the optimal shape of an SSP damper. In addition, cellular automata could be applied to other structural topological problems, including the definition of the topology of steel beams [21,22].

This research proposes a cellular automata approach to numerically optimize the topology of a steel slotted damper (SSD) from a predefined shape. Quality criteria are related to maximizing the energy dissipation capacity (EDC) for a given material area. The software Ansys is used to generate the finite element model of a given SSP damper and compute the EDC. Matlab is used to implement the optimization algorithm and connect with Ansys. It is worth mentioning that this research was carried out entirely using a numerical approach, but experimental results [23] were used to calibrate the finite element model of a vertical damper. The main characteristics of the proposed algorithm are:

- The mathematical foundations lie in the theory of cellular automata, which is used for the first time to optimize SSD dampers. This choice of algorithm was made due to the similarities between the topology optimization representation and the geometric characteristics of the damper.
- It derives an optimal topology for the rectangular-boundary SSP damper, considering the impact of the initial solution's geometry. This approach addresses the challenge of defining the best initial configuration for the device.
- It requires few assessments of the finite element model, thereby reducing the computational cost of the optimization process. Such a strategy has paramount importance due to the computational cost of the non-linear dynamic analysis.

In addition, this research discusses topics that affect the EDC prediction of an SSD damper, including its behavior under various cyclic displacements, the impact of an initial asymmetric configuration and loading protocol, and the role of the height-to-width ratio.

2. Finite element modeling of a steel slotted damper in ansys

Initially, a brief description of how steel-slotted dampers (SSDs) work to protect a building against an earthquake is presented. This explanation is supported with visual resources to ease the understanding of the problem. Typically, an SSD damper is installed in the structure as schematized in Fig. 1, where the device is directly connected to the beam in the upper part and to rigid braces in the lower part. Fig. 2 shows several examples of steel plates with various slot types and thicknesses, indicating that it is possible a huge number of possibilities. The thickness of the plate is located perpendicular to the beam axis to introduce a uniform behavior in the plate, which is assumed to be in the plane. SSD dampers are easy to manufacture, being made entirely of steel, and their installation process is straightforward for the construction industry. Therefore, these devices could be used in earthquake-prone developing countries for seismic protection because of their potentially lower cost compared to other devices.

It is worth mentioning that it is necessary to have a fully experimental characterization of the device to determine their behavior under cyclic load. In that sense, Fig. 3 presents an example of a device test, where a horizontal actuator imposes a cyclic displacement on the top of the device while the base is fixed. The main action principle is the energy dissipation of the seismic input through yielding of steel material in the plate induced by shear displacement. To achieve this, the plate thickness should be oriented perpendicular to the beam axis and have a low height-to-width ratio. After an earthquake, if the SSD is damaged, it requires a replacement. The behavior of the steel under cyclic loads has received significant attention from industry and academy, and an substantial number of devices has been proposed [24].

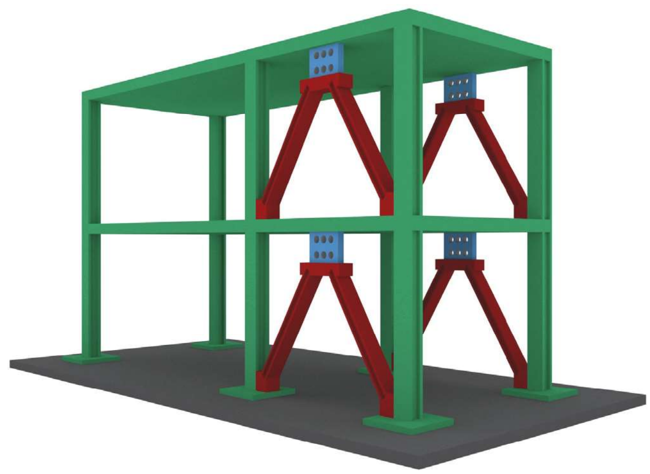


Fig. 1. SSD dampers installed on a Steel Frame.

Finite element (FE) modeling was performed using the APDL mode in the ANSYS software. This mode was selected to ease integration with the MATLAB computational routine that was developed for optimization, as shown in [25]. Fig. 4 shows the general procedure for the calculation of the energy dissipation capacity (EDC) of an SSD damper from a non-linear analysis in ANSYS and a given cyclic displacement protocol. It is assumed that the plate is thin, made of a single type of steel and that the damper is fully supported on the bottom side. Additionally, the user must provide the geometrical description of the slots. As can be seen, the FE modeling presents specifications discussed in the following paragraphs. It is worth mentioning that Ansys has previously been used in [26–28] to optimize other metallic dampers.

The first concern presented in Fig. 4(a) is the geometric description of the SSD damper. The user must define all the plate dimensions (width, height, and thickness) and slot information (location, shape, number, and size). These plate dimensions are the result of EDC requirements for a specific building project. As shown in Fig. 2, there are various possibilities for the shapes, distribution and quantity of the slot on the plate. The selection of configurations affects how the plate yields under a cyclic displacement, but there is no consensus on the procedure to define the initial configuration. The horizontal plates connect the damper to the upper beam and the lower support. It is worth mentioning that more than one type of SSD damper could be required for the different stories of the building.

The stress–strain curve that describes the behavior of the material is necessary. SSD dampers are made of ductile steel, such as A-36. Steel with low yield points can also be used [29], depending on the market availability on the construction site. This paper used a kinematic hardening assumption to consider the cyclic nature of the behavior of the steel material. Fig. 4(b) shows the bilinear representation of steel, which can be included in Ansys software. Other works have also used isotropic hardening [23] or mixed models [27], selected based on the agreement with the experimental results. In addition, more advanced phenomenological models could be used to improve the numerical assessment of the SSD Damper, see Refs. [30,31]. As there

(a) Circular slots (b) Rectangular slots (c) Triangular slots

Fig. 2. Examples of SSD dampers. Imagined by Midjourney AI.

Fig. 3. Examples of an experimental test of the SSD dampers.

is no agreement on the best model, relying on experimental results for the calibration phase of the finite element modeling is recommended.

In the process of selecting the finite element type, two assumptions are defined concerning the SSD damper: (i) the plate is relatively thin, with a uniform behavior through the thickness and (ii) the main effect is due to shear stress, not considering possible movements out of the plane. Such approach was followed previously in other works such as [13,23,32]. From the Ansys element library, the Shell181 element (Fig. 4(c)) is a 3d quadrilateral plate type element with four nodes and six degrees of freedom. In this case, the option that forced the software to consider only translational degrees of freedom was activated: KEY-OPTION(1) = 1. The Mindlin–Reissner theory is used to consider shear deformations. Other more robust elements have also been used in the literature, such as the 3D solid reported in [28]

As mentioned above, experimental testing of an SSD damper involves fixing the bottom part of the device and inducing horizontal displacement at the top. Fig. 4(d) illustrates the boundary condition defined for the model, where the entire bottom surface is fully restricted to translational movement, while the upper side is restricted only to vertical movement. These conditions simulate a relative horizontal movement between the extremes of the devices due to the difference between the movement of the upper beam and the top of the braces. The supporting braces transmit movement to the lower floor and are elastically designed to guarantee damper operation.

Despite the stochastic nature of earthquake movement, it is common practice to use a cyclic displacement protocol to assess the energy dissipation capacity of the device (see Fig. 4(e)). This protocol is imposed on the surface of the upper side of the SSD damper parallel to the beam axis. The protocol must be selected from the design code that rules on the construction site. Examples of such protocols include those defined by the documents ASCE 7-16 [33], FEMA-461 [34] and AISC [35] in the United States, as well as standards from Europe [36], China [37], and Japan [38]. The final configuration of the protocol depends on the project specifications for a specific type of damper.

Finally, it is necessary to integrate the numerical model of the device in step 4(f), as the size of the elements can influence the evaluation of the EDC. In Ansys, this process was implemented considering the default option. Table 1 shows the difference in the EDC for different element sizes for a plate. As expected, a convergence of the EDC for the lower element sizes is obtained. However, using these smaller element sizes increases the computational cost. A good trade-off between results precision and computation cost is achieved with a 2.5 mm size. For this size, the error is only 1% concerning the 1.0 mm size, but the computational time is reduced to 13%.

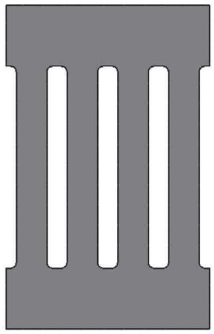
The Newton–Raphson method option in ANSYS solves nonlinear analysis in the time domain. The Line search option was activated, which improved the performance of finding the solution. Given the number of degrees of freedom in the FEM model of the damper, the Sparse Direct Solver was used for a more efficient algorithm. After the analysis, a post-processing stage is necessary to determine the Von-Misses stress state, the distribution of deformation energy, and the hysteresis cycles in the devices, as shown in Fig. 5. ANSYS directly computes the total deformation energy, which helps to assess the objective function during the optimization process.

3. Shape optimization of SSD dampers

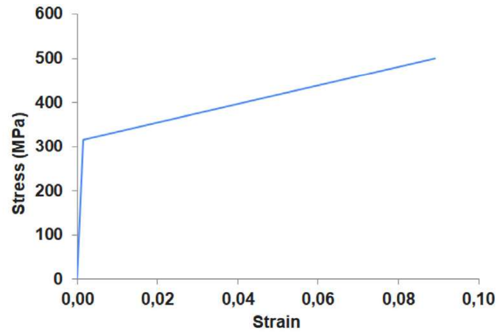
Changing the shape of the slots on a steel plate is manufacture-friendly due to the simple configuration of the damper, as seen in Fig. 6. For the regular and basic slot configurations, it is possible to keep the same quantity of material, inducing a different energy distribution density for each configuration, as seen in Fig. 7. In addition, the height/width ratio affects the energy/mass ratio as the stress trajectories on the plates change during the cyclic movement. In that sense, it raises the question: ¿what will be the plate's shape that maximize the energy dissipation capacity during an earthquake movement?.

An optimization problem is configured to determine the optimal shape of the damper that maximizes its efficiency in dissipating seismic energy. Two types of computational problems are derived, depending on whether the amount of material can vary during the optimization process or not. Fig. 8 presents the case of the two types of optimization for an SSD damper with vertical slots. Fig. 8c shows that the material changed from the initial condition to an optimized shape. This is because the change in the mass could help to better exploit the energy dissipation. In 8b, the quantity of material is fixed. This condition obliges the algorithm to ensure that the quantity of material does not change between two consecutive iterations. It is worth mentioning that the user must define an initial configuration for the SSD damper in both cases. The symmetry concerning a vertical and horizontal axis through the plate's center point is generally considered to reduce the computational complexity of the problem. The final boundary of the plate significantly affects its overall behavior. Therefore, it is possible to use an interpolation function, such as B-Splines [39], to indicate how that transition should be.

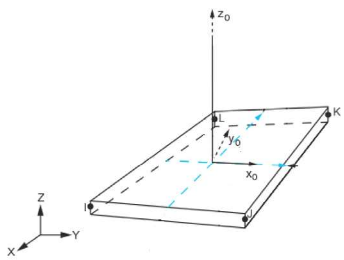
In the FE model of the damper, each element in the mesh discretization is assigned a binary value: zero for a void and 1 for a material point. For SSD dampers, a rectangular domain for the plate is assumed, with the mesh size defining the number of positions to be specified. Fig.



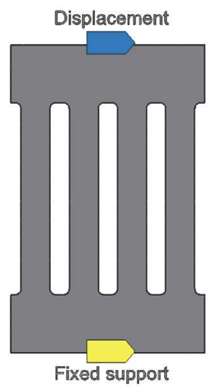
(a) Geometrical information



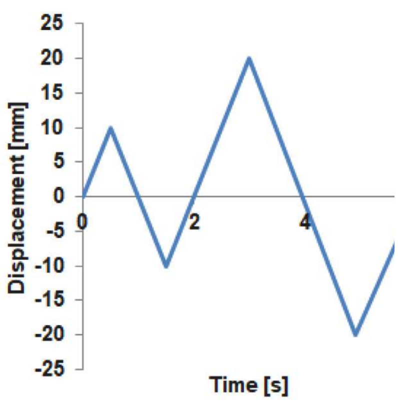
(b) Material



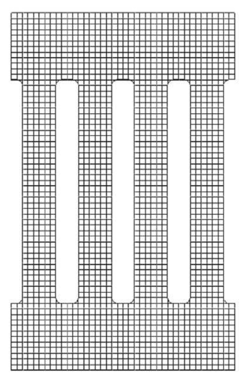
(c) Type of finite element



(d) Boundary conditions

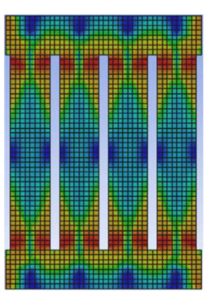


(e) Cyclic displacement protocol

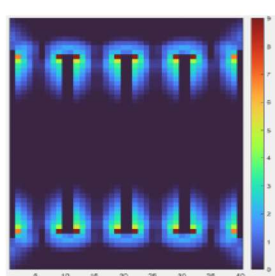


(f) Meshing

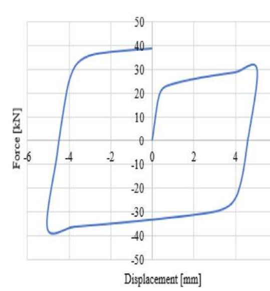
Fig. 4. Scheme of the finite element modeling of a SSD damper under a cyclic displacement protocol.



(a) Stress



(b) Energy distribution



(c) Hysteresis Cycle

Fig. 5. Example of post-processing.

Table 1
Impact of the mesh size on the computed deformation energy and the computational cost.

Mesh size (mm)	Deformation Energy (J)	Computation Time (min)	Difference (%)
1.0	1097	15.0	–
1.5	1100	7.0	0.27
2.5	1109	2.0	1.09
5.0	1125	0.5	2.05

Fig. 6. Examples of slotted damper.

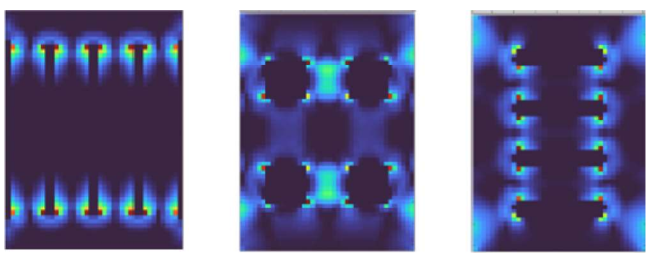


Fig. 7. Examples of energy distribution.

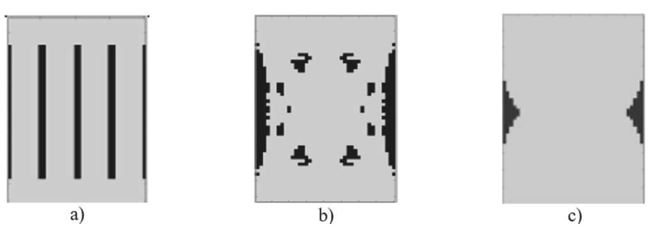


Fig. 8. Examples of energy distribution.

9 illustrates four computational representations, each corresponding to a different initial configuration of slots. As the topology changes during the iterative process, a strategy is needed to ease the finite element meshing. In this approach, voids are represented as material points with a very low modulus of elasticity. Therefore, the same mesh discretization is used in each iteration. The only constraint is that the elements must remain within the original boundary. Some studies use a one-cycle protocol [23] to determine the optimal shape [23] with the aim of reducing the computational cost associated with the optimization process. However, it is necessary to account for the effect of multiple cycles, as shown in [40].

Several metaheuristic and gradient-based approaches have been reported in the literature, which gives information on the optimal shape of a damper manufactured from a steel plate with slots. The gradient-based approach considers the computation of the derivatives of the energy dissipation function, as observed in [23,41]. In addition, it is possible to determine only the variation of the plate boundary, as presented in Ref. [40]. Metaheuristics approaches have been followed to ease the optimization process, highlighting algorithms such as Simulated Annealing [13] or Grey Wolf Optimizer [42]. The cost computational is critical when choosing the metaheuristic type, which is a disadvantage for a population-based metaheuristic. The majority of the optimal shapes obtained correspond to hourglass shapes for the slots [13,23]. An optimization algorithm could get stuck in a local optimum depending on the original configuration of the SSD damper, as shown in Ref. [13]. It is worth mentioning that there is no benchmark study to define the global solution for the SSD damper in a building, which implies further research.

4. Concept of celullar automatas in topology optimization

Cellular automata (CA) comprise a network of identical cells (slots) with an assigned state that can be represented in one or more dimensions. Each cell interacts with its defined neighbors and has a set of possible states, such as a black-and-white strategy. The state of each slot evolves by applying a set of local rules that consider the current state of the cells and those of its neighbors. It is worth mentioning that the application of the rule is carried out in parallel, accelerating the computations. This concept is illustrated in Fig. 10, where simple rules lead to the development of complex behavior in the popular game of life. That property of CA can be used to apply problems in different fields of knowledge such as spread of infectious diseases [43], management of evacuation from a sporting event [44], organizational management [45], music composition [46], understanding online public opinion [47] and protection of the Internet of Things [48]. Fig. 11 shows an example of a CA in nature, a typical distribution for a 3D structure, and a CA-based civil structure. The question now is how to use the CA technique to solve a given problem with specific characteristics. Detailed information on the conceptual and mathematical aspects of CA can be found in references such as [49,50].

There is a natural comparison between the CA 2D array in Fig. 10 and the optimization of the topology of a simply supported beam under a vertical load in the center. This is because the finite element mesh defined for a structure can be formulated in terms of voids and material points. Then, it is important to define a strategy for evolving the structure to its optimal shape. Hybrid CA [20] is an alternative for optimizing the mechanical topology of a solid structure by discretizing the physical domain into a regular array of CA. The state of the ith automaton is related to the presence or absence of material in the corresponding location, x, representing the CA mass. It also defines the state value corresponding to the stimulation of the CA. The state of the variables is assessed from the finite element analysis, which reduces the residual between external work and the internal energy to zero for each interaction. Each automaton locally modifies the design state variables until they reach the optimal value. This means that the rules aim to minimize the absolute error between the energy density of local deformation and the objective value. The algorithm begins with defining the design domain, the material properties, the load conditions, the boundary condition, and the initial values of the design variables. Then, the initial value of the state variables is computed using the finite element analysis of the structure. The evolution rule is applied to modify the design variable. Then, the convergence of the process is verified after no improvement is observed.

Fig. 12 presents an example of the application of the hybrid CA to a simply supported beam with a vertical load in the middle as proposed in [20] and which the authors implemented to assess its correct application. The method requires a posterior discretization