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Research Paper

Shape Optimization of Slotted Steel Plate Dampers using the Simulated Annealing Algorithm

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Abstract. This paper reports a procedure for maximizing the energy dissipation capacity (EDC) of a slotted steel plater damper by changing its initial geometrical shape. The methodology uses a simulated annealing algorithm to iteratively vary the slots' disposition, number, and geometry while improving the EDC. This capacity is computed for each tested configuration from a finite element analysis in ABAQUS, considering a cyclic displacement protocol. Five initial sections are enhanced, with the optimal one evoking a sand clock shape with two symmetric slots. The EDC increment is higher than 300%. It is observed that the objective function is multi-modal, and the optimal solution depends on the initial design. The proposed procedure is computationally easy to implement and requires less than fifty iterations to guarantee convergence in all cases.

Keywords: Metallic dampers, shape optimization, simulated annealing, slotted plates.

1. Introduction

The use of seismic protection devices (SPDs) in buildings has become a reality in several countries around the world (see reference [1]), representing an alternative to the conventional seismic design based on energy dissipation through the inelastic behavior of the structure. Introducing SPDs in a structure makes it possible to avoid the elements in the primary seismic force-resisting system suffering considerable damage in large earthquakes, increasing the structure's seismic performance and reducing the cost associated with repairs and loss of human lives. These devices can be classified into active, passive, hybrid, and semi-active devices according to the nature of their behavior [2]. Passive devices are preferred due to their low price; nonetheless, they cannot modify their properties in function of the seismic input. Japan presents more than 3000 buildings protected with seismic isolation, showing that the culture concerning the seismic hazard is essential [3]. In the United States, more than 350 structures have been equipped with buckling restrained braces since their introduction in the 1990s [4]. In addition, the company Quaketek has provided friction dampers for more than 50 structures worldwide in countries such as Canada, the United States, and Colombia [5]. There are many seismic protection devices; however, numerical and experimental research is being carried out to develop new devices that either reduce the seismic response during a seismic event or decrease their cost. It is worth mentioning that other strategies, such as self-centering devices, can efficiently minimize structural damage, as shown in [6].

A specific strategy to mitigate seismic damage in a structure consists of fuse elements that dissipate energy by concentrating inelastic displacements in hysteretic cycles. Different ways exist to use the movement during an earthquake to counter its effects, such as material yielding or friction. Typical Buckling Restrained Braces have a steel core with a yielding zone that concentrates the inelastic deformations in the element. A concrete cast guarantees that the performance of the braces is equal in compression and tension and the occurrence of stable cycles of hysteresis [7]. Friction dampers present a mechanism that dissipates energy through the sliding of two surfaces in contact due to the differential movement on each side supporting the damper; this happens after a pre-specified sliding force in the damper is achieved [8]. Metallic Yielding Dampers use inelastic displacements to generate energy dissipation in the whole device; one example is the triangle-added damping and stiffness (TADAS) damper [9]. Yielding could be raised by flexure, or shear stresses over the damper material. The design of a structure equipped with hysteretic-type dampers is ruled by international norms, such as ASCE 7-16 [10]. This code reports the experimental test required to guarantee the reliability of the devices, including the procedures to consider uncertainties in damper parameters in the structural analysis.

The slotted steel plate (SSP) dampers are configured for thin steel plates parallel to the beam. These dampers are hysteretic-type devices that dissipate energy when the steel yields due to the deformation introduced by the relative movements on the top and bottom of the devices (shear forces effect) during an earthquake. Experimental results on a cyclic test of individual specimens show that SSP dampers present regular and symmetric hysteresis cycles, even for large deformations [3]. This characteristic guarantees the reliability of the performance of the devices. However, research has shown that the dampers suffer a gradual strength reduction due to the beginning of flexural cracks in the slots' boundaries [11]. The use of SSP Dampers in structures has helped reduce their seismic response. Li et al. [12] reported levels of 90% in the reduction of the displacement of a reinforced concrete frame on the base floor when using a damper with an x-shape. Pimiento et al. [13] showed displacement reductions of up to 70% in a shaking table test of a three-story scaled steel frame using SSP dampers with circle and rectangle slots. Martinelli et al. [14] reported that low-cycle fatigue is a criterion that conditions the seismic response of a retrofit-reinforced concrete building. There is a high correlation between the top displacement and the seismic damage index of a structure. Teruna et al. [15] found that a trilinear approximation for the skeleton curve was adequate, being necessary to define two constants to describe the post-yielding behavior. On the other hand, the manufacture of this type of device is not complex and not expensive. Its installation on the structure is not complicated; therefore, they are very suitable for developing countries.

One of the aspects that influences the plates' energy dissipation capacity (EDC) corresponds to the shape, distribution, and quantity of slots. Chan et al. [5] found that the amount and distribution of circle slots influence the distribution of Von Mises Stresses through the plate and that the stress trajectory affects the zones where the yielding occurs. Zheng et al. [16] compared four distributions for vertical slots finding that this parameter affects the stability of the hysteretic cycles. Ferrer and Villalba [17] studied a set of plates with different shapes and found that the lowest and highest EDC difference could be up to 300%. Thus, it is possible to configure an optimization problem to determine the optimal topology for the damper to obtain the highest EDC from an available volume of steel material. Ghabraie et al. [2] optimized the shape of a rectangular slot through the BESO algorithm; they found an increment of up to 96% in the EDC. As a result, the stress distribution was improved. Xu et al. [18] optimized the boundary of honeycomb mild steel slit dampers by considering that each strip works as a bi-clamped beam under pure bending. Other research involving the optimization of metallic-yielding dampers were carried out by Watanabe et al. [19] and Deng et al. [9], obtaining the best position of stiffener elements in the damper. Both works showed that the optimal configuration for the damper presents a higher EDC. Liu and Shimoda [20] used Bezier Curves and an objective function based on the maximum cumulative equivalent plastic strain on both sides of the damper, with the constraint that the dissipated energy of the optimized shape is greater than the initial. Zhu et al. [21] compared two optimization criteria based on the J2 Plasticity theory considering that all the points on the contour yield simultaneously, finding that the energy dissipation capacity increased between 40.65 and 63.69%. Farzampour et al. [22] used the Gray Wolf Algorithm to determine the optimal shape of butterfly-shaped shear links by maximizing the energy dissipation ratio by plastic deformation to the maximum equivalent plain strain.

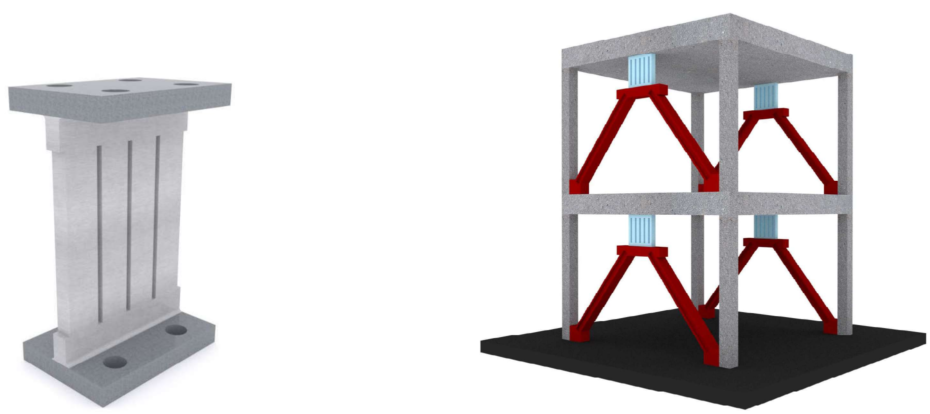
The results above show that optimization is suitable for developing improved damper configurations. Notwithstanding, the selection of the optimization algorithm, either a heuristic or gradient approach, and the influence on the initial geometrical configuration of the damper are some issues that require further attention. This study presents a heuristic-based methodology for the shape optimization of SSP dampers based on maximizing the device's EDC, which can be applied to different initial shape dampers. The software ABAQUS is employed to compute the EDC of each shape tested under cyclic load. As this procedure presents a high computational cost, the Simulated Annealing Algorithm (SAA) is used to solve the optimization problem as it requires only one solution per iteration. Python is used to implement SAA and to get interaction with ABAQUS.

This research is significant because of the following reasons:

- It establishes a new shape for the SSP damper that presents the highest EDC for any given steel material quantity.
- It reduces the complexity in the computational implementation by using a free-of-derivatives algorithm, considering the interaction with Python and ABAQUS.
- It uses problem-knowledge heuristics to improve the convergence process.
- It assesses the influence of the SSP initial shape on the optimal result obtained by the optimization process.

2. Slotted Steel Plate Dampers

The working concept of such devices is quite simple; by introducing plastic deformations on Steel plates, it is possible to dissipate the seismic input energy. Different movement types could generate yield in the material, such as pure flexion, pure shear, and combined stresses. However, how the yielding is raised is not the only matter; it is essential to ensure that most of the device effectively yields and that the threshold of inducing deformation presents a minimum possible. The slotted steel dampers work mainly under shear stress, so they are formed by a thin perforated plate, such as the plate with vertical slots shown in Fig. 1a. It is possible to select several shapes for the slots, such as circles, triangles, or rectangles. Still, it is necessary to establish the optimum shape as the slots' shape, number, and position affect the sequence of how the strains will distribute on the plate. Figure 1b shows how the plate is installed into the structure with the thickness located perpendicular to the beam. The upper side is connected to the beam, while the lower side is connected to braces in a Chevron Configuration. Such configuration eases the relative strain between the device's top and bottom, inducing shear stress in the damper. However, it is necessary to guarantee that the plate does not present buckling perpendicular to the beam, reducing the device's effectiveness. There are different stiffener types to avoid out-plane buckling, such as the device proposed by Deng et al. [23]. The design of the primary seismic-force resisting system and the energy dissipation system have to guarantee that the SSP dampers yield first than the structural elements, as shown in the methodology proposed by Oviedo et al. [24]. It is worth accounting that the device and its connected components increase the structure's stiffness; thus, it could increase the shear force on the building. The attractiveness of using these devices is their manufacturing simplicity, low cost, and the possibility of being easily replaced after an earthquake (it works as a fuse).



(a) (b)

Fig. 1. Example of a Steel Slotted Plate (SSP) damper: a) individual device and b) installation on a structure.

Different metallic materials can dissipate energy, such as steel and aluminum. Most papers deal with A-36 steel due to its yielding properties: low-yielding point and ductility. Yongjiu et al. [25] carried out a cycle test on A-36 steel specimens of 200 mm length, finding that the failure mode at a macro level corresponds to the contribution of the central region, buckling, and fracture; with a ductile failure in a micro level. However, researchers explore low-yielding point steels to decrease the device's deformation level to start dissipating energy [26]. Concerning the failure mode, it is observed that low-cycle fatigue can occur in high-stress concentration points. Jie et al. [27] experimentally show large deformations in the edges of slots due to the high stress in this zone raised in the shape of the damper. Perri et al. [28] showed that different steel types could present fatigue in different load cycles, observing that the area of the hysteretic process reduces in the cycle next to failure. Bae et al. [29] observed that including plastic hinges into a radius-cut coke-shaped strip damper resulted in higher ductility. Under the above findings, the challenge in numerical modeling is reproducing the results. For example, the definition of the constitutive model is an open question. Recent research show that different models could be adequate from experimental results [30]: Bilinear with isotropic hardening, Bilinear with kinematic hardening, trilinear, and Chaboche model.

To assess the ability of an SSP damper to dissipate energy is necessary to carry out a pseudo-cyclic test that introduces cyclic displacements in the upper surface of the damper while the bottom part is fixed. By doing that, it is possible to induce shear stress using load cycles established according to the protocols of documents such as EN-15129, ASCE 7-16 chapter 18, or FEMA 751. These documents also report how to include results coming from several tests. It is worth mentioning that the test of a device causes it to yield; therefore, it cannot be used in any building after testing. Furthermore, numerical integration on displacement and force measurements is used to compute the EDC. From a numerical point of view, this is possible by integrating the stress vector (f) and the displacement field (u) on the whole plate domain, as given by

$$E_p = \int f \times du \tag{1}$$

On the other hand, the following questions have to be raised when using SSP dampers: How will strains be induced in the device from their connection to the primary structural system? What shape will the slots of the device and outer edge have? What type of steel can be used? How can the device's performance to reduce the seismic response be computed? What are the protocols for the experimental test of the devices? What is the reliability of their performance under low-cycle fatigue? Which constitutive model will be used in the numerical model? There is no consensus in the literature on some of these aspects; a more detailed study is necessary to collect the current knowledge to address the main path to follow. A comprehensive state-of-the-art on hysteretic steel dampers can be found in the paper by Javanmardi et al. [31]. The present research has only a numerical phase; thus, the decisions on the above questions were taken from the literature.

3. The Simulated Annealing Algorithm

The Simulated Annealing Algorithm (SAA) is a stochastic heuristic method to solve search problems developed by Kirkpatrick et al. [32]. The algorithm follows an analogy of the principle of annealing metal materials that associates the best solution for an optimization problem with that state of the material without imperfections. Material perfection is achieved by slowly reducing the temperature to a lower energy state. Thus, a single solution is modified around its current neighborhood to generate better solutions and guide the search process. The main issue with SAA is the possibility that the algorithm will advance to a worse system state to prevent stagnation.

Figure 2 presents a typical flowchart for applying the SAA to solve an optimization problem defined by the objective functions, design variables, and constraints. The algorithm starts the iterative process by defining a single solution vector named design solution, randomly generated from the allowed values for each variable in the problem. First, the user must provide an initial value for the temperature parameter (T), which ranges from 0 to 1. The parameter determines if a trial solution is accepted as the design solution. Then, the trial solution is generated from a probabilistic expression that modifies the design solution inside a close space. Then, the objective function is computed, and the acceptance criterion is applied. The criterion compares a 0-1 random number against the acceptance probability (P), which is given by:

$$P(\Delta f, T) = e^{(\Delta f / T)} \tag{2}$$

where Δf is the difference between the quality of the trial and design solutions. High values of the temperature factor increase the probability that a trial solution is accepted even if it is worse than the current design solution. This characteristic is fundamental to avoid the algorithm getting stuck in local optimums. The trial solution becomes the design solution if the acceptance criterion is satisfied. The algorithm completes the process when a stop criterion is achieved, for example, when a maximum number of iterations is met. However, it is necessary to execute the algorithm in a predefined number of runs due to the stochastic nature of SAA.

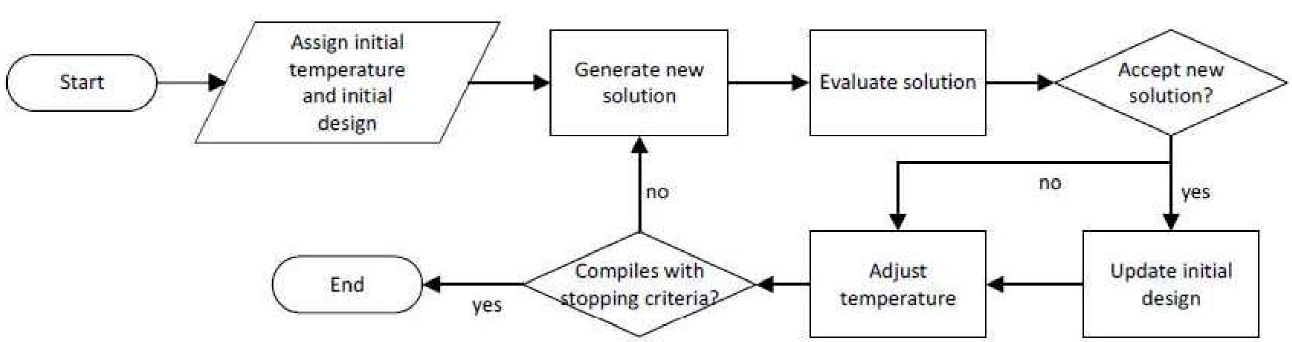


Fig. 2. Traditional Simulated Annealing Algorithm.

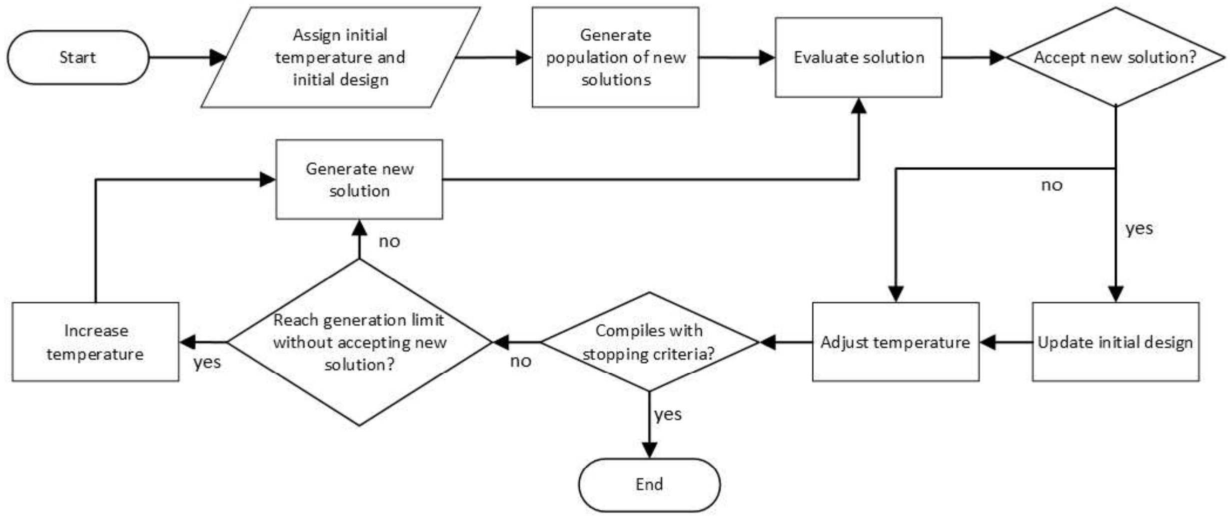


Fig. 3. Modified Simulated Annealing Algorithm [29].

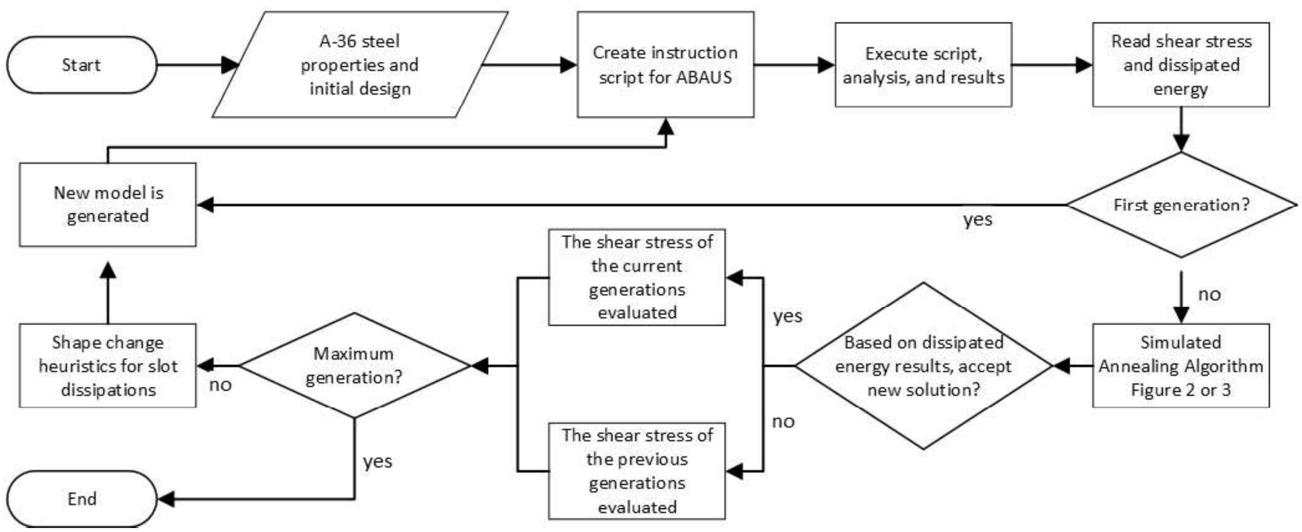


Fig. 4. Algorithm for the shape optimization of Slotted Steel Damper with a SAA and Abaqus.

Milan and Begambre [33] introduced three modifications to improve the performance of the SAA in terms of the final result and lower computational time. The first one is related to the fact that the current expression for the acceptance probability takes the algorithm more iterations to converge. In that sense, the following equation reduces half the probability of accepting a solution.

$$P(\Delta f, T) = \frac{1}{1 + e^{(\Delta f, T)}} \tag{3}$$

The second modification decreases the dependence of the original SAA on the chosen initial design solution, as any other answer is a variation of that solution. Thus, the first trial SSP damper configuration corresponds to the highest objective function from a pool of randomly generated initial design solutions. Finally, the third modification introduces global exploration for high temperature and exploitation (local exploration) for low temperature by modifying the mutation factor used to generate the trial solution. The last modification considers that the mutation factor can change but in the function of the temperature factor. If the algorithm detects that it could be stuck in a local optimum, then the temperature will go up with the mutation factor to increase the ability to explore the search space. Figure 3 shows the flowchart for the modified SAA (MSAA) considering the above changes, as in reference [33].

It is worth mentioning that no metaheuristic method can efficiently solve all the optimization problems. Still, the SAA has proven its capability to solve different structural engineering problems. Some of these problems correspond to structural damage detection [34], structural size optimization [35], the optimal location of viscous dampers [36], and the optimal position of sensors for modal identification [37]. The necessity for adjusting SAA to the characteristics of each problem implies that the user has to know how to modify the computational implementation.

4. The Proposed Methodology for the Optimization of Slotted Steel Dampers

This research proposes a methodology to obtain the optimal shape for an SSP damper (see Fig. 1) that maximizes the dissipation energy capacity under cyclic load given a specific quantity of material in a predefined initial shape. The flowchart to apply the methodology is presented in Fig. 4. It is based on the interaction among finite element modeling software, the mathematical function of the optimization problem, and a search algorithm to solve the problem. It is necessary to carry out a dynamic non-linear finite element analysis for the plate suffering the cycles of seismic loads to determine its hysteretic behavior and later compute its EDC. In this case, the Software ABAQUS was used for numerical modeling. It allows the assessment of the plates' behavior under large deformations and the interaction among the different components of the algorithm. The mathematical formulation for the optimization problem is given in section 4.1 and requires to be implemented computationally, including some extra information derived from Abaqus. The optimization algorithm followed a heuristic approach as it facilitates introducing computational procedures to account for the problem knowledge (see section 4.3). The MSAA in Section 3 solved the optimization problem due to its convergence properties and a single-population algorithm. These characteristics are fundamentals to reduce the computational cost associated with applying the proposed methodology, as each possible solution tested implies one run of finite element analysis. The routines and the interaction with Abaqus were implemented in the programming language Python to assess the performance of the proposed methodology.

The search process of the device with the optimal shape is iterative, beginning from an initial plate configuration to obtain an enhanced plate in terms of its energy dissipation capacity. The user is faced with defining the quantity of material to manufacture the plate and its initial shape, which plays a crucial role in the optimal shape obtained. The MSAA could easily get trapped in a local optimum because the search space for the problem is multi-modal; this means that very different shapes for the plate can present similar values of the objective function to that of the global solution. Section 4.1 offers the computational representation for each damper. The steel used could also lightly affect the optimal shape, requiring an independent optimization process for each type. The results of this paper were obtained using a steel A-36, a common type of steel worldwide.

It is necessary to generate an Abaqus script to carry out the finite element modeling of the damper, as shown in Section 4.4. The modeling implies that the user has to provide the element type, the maximum size of the finite element mesh, constraints, constitutive model, type of analysis, load pattern, and desired results. The computational code executes the script in Abaqus, obtaining the time-history response of the plate to a predefined cycle load in terms of stresses and deformations. An additional code is implemented to compute the energy capacity dissipation of the damper.

The displacement cycle used to determine the plate's EDC was proposed by Ghabraie et al. [2] and carried out in four steps, as shown in Fig. 5. First, the plate starts from the position related to the initial configuration. Next, a displacement of 10 mm in the right top is applied, followed by a 20 mm displacement in the opposite direction, then the plate returns to its initial position. Finally, the lower side is kept restricted from movement. Such representations simulate the relative displacement between the support (on the damper's downside) and the beam (on the upper side). The superior boundary is only restricted in the vertical direction.

Then, the modified SAA in Section 3 is applied to the mathematical optimization problem defined in Section 4.1 after the user defines its parameters (see Section 4.2). A total of five trial plate shapes are derived from the initial design, with the trial solution being chosen as the plate with the larger EDC. The equations for generating the trial solutions are presented in Section 4.3. The algorithm is stopped when a maximum number of iterations is achieved. As the MSAA is stochastic, a predefined number of generations of runs is carried out to define the best solution.

The characteristics of the SSP damper used in [1] are analyzed to verify the proposed finite element modeling and the computation of the EDC (see Fig. 6), with L, R, and H being the damper's width, thickness, and height, respectively. E and X are the slot's width and the plate connection's thickness, respectively. In addition, the information would be used to generate a new set of initial solutions to verify the dependence of the optimized shape on the initial configuration. Finally, the performance of the proposed methodology is compared with those reported in the mentioned paper.

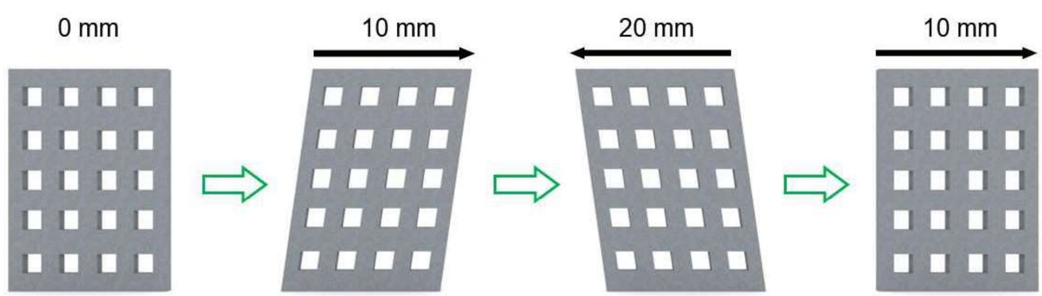


Fig. 5. Cyclic displacements for the loads.

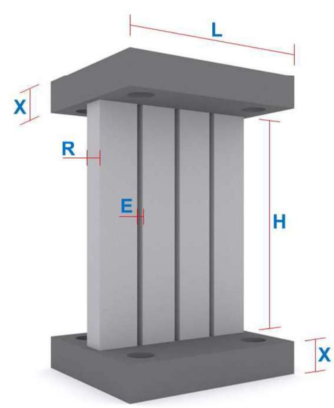


Fig. 6. Slotted Steel Plate Damper of reference proposed by Ghabraie et al. [2].