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TECHNICAL PAPER

A proposal for the optimization of the geometric configuration of a hollow cylindrical steel damper with slots

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Abstract

The energy dissipation capacity (EDC) of most current configurations of yielding steel dampers is susceptible to be improved by applying optimization concepts. Thus, this study proposes a methodology to enhance the EDC of a slotted hollow cylinder steel (HCS) damper under a cyclic displacement protocol while keeping the same quantity of material via shape optimization. The simulated annealing algorithm was selected for solving the optimization problem as it uses only one candidate solution per iteration, reducing the computational cost associated with the EDC computation. In addition, the finite element software ABAQUS is used to model the behavior of the steel damper under cyclic loads. A code is elaborated using the Python programming language for the optimization process, containing the instructions to be executed in ABAQUS. Five slot configurations were proposed for the initial damper to determine the effect of the initial solution on the optimized HCS damper. The results show that the proposed optimization process obtains optimized models with stable hysteretic behavior and a significantly higher energy dissipation capacity than the initial models. The optimal configuration presented an EDC of 5543 J, 16% higher than the HCS damper without slots and with the same material quantity. The material is mainly located parallel to the beam, simulating two 2D shear steel plates. The difference in EDC with other optimized configurations reaches 955 J, indicating the dependence of the solution on the initial damper configuration. In addition, the difference in the optimized damper topologies proves the multi-modality characteristic of the problem. The proposed algorithm is easy to implement in a computer and reaches the optimal solution with less than 50 iterations.

Keywords Hollow cylinder steel (HCS) damper · Shape optimization of dampers · Simulated annealing · ABAQUS

1 Introduction

The possibility of using the yield of metallic material through hysteresis cycles to dissipate seismic energy has gained attention over the last decades in developing seismic protection systems. The mechanical principle of metallic hysteretic dampers is to dissipate energy through the inelastic strains induced in the device during the seismic movement. Thus, the material used in damper manufacturing should present a low cycle yield point to initiate the yield process with a low level of stress and large ductility to guarantee important energy dissipation. So, many energy dissipation devices have been manufactured from metallic materials such as steel, aluminum, lead, copper, and some memory-shape alloys, with each material presenting its own characteristics. Low-yield point steel is preferred because it allows several inelastic cycles before total failure [1]. Copper is suitable for protection against impulsive-type earthquakes but presents a high cost [2]. Aluminum has lower yield

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points and more significant ductility than steel [3]. Lead has recrystallization properties that help it recover its original internal structure after an earthquake, preventing the device from being replaced [4]. Shape-memory alloys allow recovering the device form after using it during a seismic event and have excellent behavior to environmental factors [5], with Tabrizikahou et al. [6] presenting a complete review on the subject. Most metallic hysteretic (MH) dampers show the following characteristics: (i) displacement-depending behavior with stable hysteretic cycles, (ii) a low-cost associated with their manufacturing, and (iii) strength to the environment [7]. However, it is worth considering that the final behavior of the devices can be influenced by factors such as the Bauschinger effects [8], the possibility of buckling [9], and low cycle fatigue [10].

The MH dampers are typically located on braces connected to the main structure so that the relative movement between two stories induces inelastic strains in the device. Depending on the geometric configuration, these strains could be raised by axial, flexure, or shear effects. For example, the yield of the steel core in buckling restrained braces is induced through the axial forces generated in their extremes [11]. The geometrical shape of a TADAS device and the hinges in the lower part cause inelastic displacements by flexure [12]. Nonetheless, it is possible to induce shear stress in perforated steel plates by locating the thickness perpendicular to the beam [13]. Other modifications of the devices allow combining the shear and flexure effects to obtain a higher energy dissipation capacity (EDC), such as in reference [14]. Therefore, it is possible to guide a search process for the best metallic damper shape by understanding the stress trajectories on the device in the presence of several load reverse cycles. To the authors' best knowledge, a unique criterion for determining which geometrical configuration is the most outstanding, under the material or cost-based constraints, is unavailable. A simple criterion would correspond to the ratio between the EDC and the material quantity used in the device. A more complex criterion would be the device's cost (including the manufacturing process). On the other hand, no study generates a framework to compare the different available damper's geometrical configurations fairly.

Optimization is one strategy for determining the damper geometrical configuration that produces the highest EDC. There are different strategies to apply optimization to the mentioned problem: (i) to compute the dimensions of the device if the geometric configuration is known, (ii) to obtain the topology of the device from a user-defined initial configuration while keeping the material quantity constant, and (iii) to define the minimum quantity and distribution of materials to achieve a specific EDC. Most research follows the second strategy with application to slotted plate steel (SPS) dampers and considering maximizing the EDC. Ghabraie et al. [15] presented in 2010 one of the first papers to optimize an SPS damper from the gradient-based method, obtaining an increment in the EDC of 1124–2203 J for an initial configuration with horizontal slots. Park et al. [16] use the sequential quadratic programming method to derive an optimal shape for a metallic damper with application to bridges. In addition, the problem definition could include a smoother function for the boundaries that generate better computational modeling of the devices and a reduction in the number of variables [17]. The possibility of using a computer-aided design to create shapes and isogeometric analysis has increased the feasibility of obtaining better devices [18]. In brief, a correct definition of the stress state plays a critical role in the optimization process. Farzampour [19] shows the optimal solution could be affected by the presence of a combination of flexural and shear stresses in a butterfly-shaped damper by considering a Von Mises criterion.

On the other hand, it is possible to use nature-based optimization algorithms in the shape optimization of yielding steel dampers as an alternative to ease the mathematical representation of the problem. Khatibinia et al. [20] used the particle swarm optimization algorithm to obtain the optimal shape of a U-shaped steel damper, using a support vector machine model to reduce the computational cost related to the finite element analysis. Kiani et al. [21] configured a Tabu search algorithm to solve a multiobjective approach where the low-cycle fatigue and the EDC are considered simultaneously. Kim et al. [22] employed the whale optimization algorithm to determine the best shape of a curved steel damper, supported by a B-splines-based strategy for defining the damper boundaries. Ferrer and Villalba [23] used a binary model to indicate the presence or not of material, which allowed the generation of heuristics to improve the convergence process. Independent of the type of algorithm, the optimization process will need to interact with a finite element software, such as ANSYS [24] or ABAQUS [25], to determine the behavior of the devices under the cyclic load.

This paper generates the numerical shape optimization of an HCS damper with slots from a nature-based metaheuristic. The HCS damper was selected in this research as it proved to have a good capacity for energy dissipation [26]. The optimization process was based on that proposed in [23] but used a conventional simulated annealing (SA) algorithm, which had an excellent convergence behavior. The SA algorithm is chosen as it has proved its value in other problems of the structural engineering field and uses only one solution per iteration, reducing the computational cost. The initial slots' shapes were selected from simple geometrical forms; vertical slots are commonly used in the literature, as in reference [15]. The main contributions of the current research are related to the following issues:

- The obtained results represent the first attempt to optimize the HCS damper;
- A specific representation scheme was proposed to computationally represent a damper configuration, which allows analyzing the tridimensional plate through a bidimensional binary array;
- The use of the SA algorithm proved to reach feasible solutions with few iterations;
- Including problem-knowledge-based heuristics in the computational strategy accelerated the convergence process;
- Several initial configurations for slots were tested to determine their influence on the optimized solution;
- The procedure could be easily adapted to other metallic hysteretic dampers working by shear.

Even though this research is numerically developed, results in [21] were used to calibrate the finite element simulation. Finally, the study is limited to determining the structural behavior of the HCS damper working separately under one cyclic displacement-based protocol. Therefore, the computation of the seismic response of a primary structural system equipped with the device under seismic loads will be carried out in future research.

2 The hollow cylinder steel (HCS) damper

The HCS damper is a seismic protection device introduced by Abebe et al. [26], which dissipates energy through the yielding of the material induced by the displacement relative between the upper and bottom parts during an earthquake movement. Therefore, the device should be made from steel with low yield points and good ductility, such as A-36. Figure 1 presents the material distribution for the device, whose radial symmetry allows better behavior in two orthogonal directions. Its standard installation on braces in Chevron configuration is illustrated in Fig. 2 for a one-story steel frame. Typical values for H are between 2.5 and 4.5 m, while L is between 6 to 10 m. It is worth mentioning that the main application of MH dampers is in buildings, but they have also been applied in bridges [27]. For example, Javanmardi et al. [28] present the simultaneous application of a hexagonal honeycomb steel damper with a lead-rubber-bearing isolator to control vibrations in a cable-stayed bridge.

From a theoretical point of view, the device could be structurally analyzed as fixed at the bottom part and loaded with a displacement protocol in its upper side (free extreme), introducing stresses in the device due to a combination of flexure and shear. Abebe et al. [26] determined that the effective aspect ratio (height/diameter) to produce the best performance is $\sqrt{3}$. Higher ratios result in a predominant flexure failure, while lower ratios induce shear failure. Utomo [29] added metallic reinforcement in the device outward to avoid strain concentrations in the support element, increasing the number of supported load cycles. Kim et al. [30] experimentally observed that the cylinder damper could adequately support bidirectional loads, with a failure initiated in the weld toe. Such results prove the value of cylinder dampers to dissipate the energy induced by an earthquake in a structure but raise the question if the device could be improved.

One possibility to increase the device's performance is by introducing slots because they modify the stress trajectories inside. Figure 3 presents the original HCS damper in the middle and two configurations with slots, while Fig. 4 shows the stress distribution for induced cyclic displacement energy. The differences in such distributions imply that the dissipated energy was different for the event, raising the question: Which is the best shape configuration for the slotted HCS damper that produces the highest EDC? The methodology presented in Sect. 3 tries to answer the above

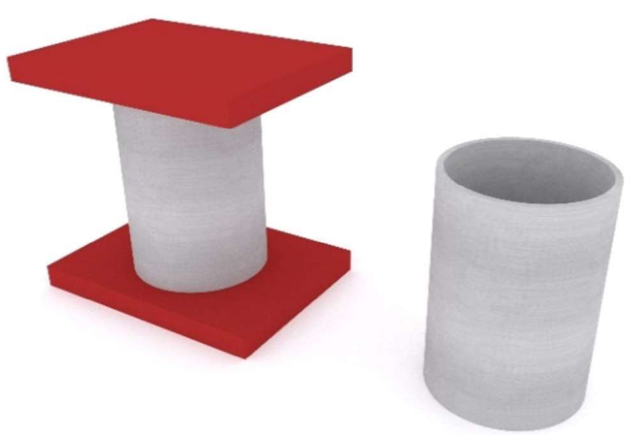

Fig. 1 HCS damper

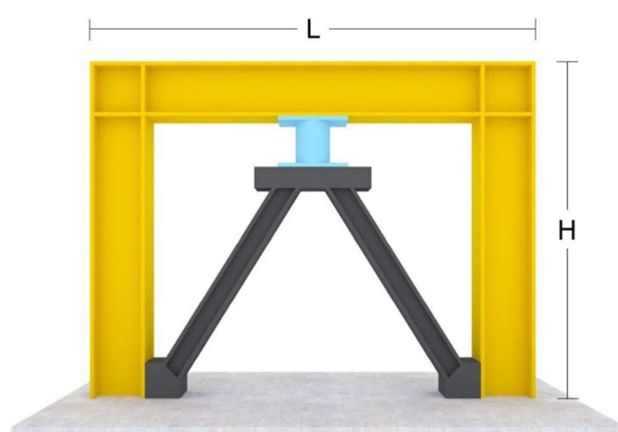

Fig. 2 HCS damper in a one-story steel frame

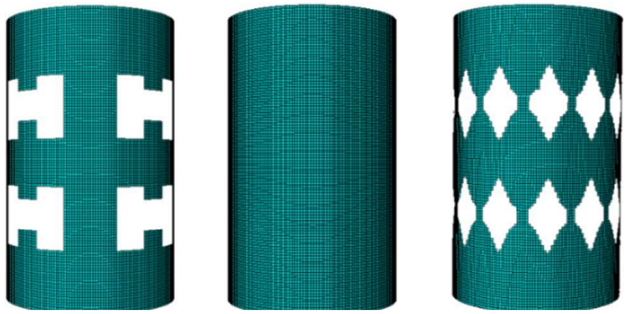

Fig. 3 Different configurations of the HCS damper with slots

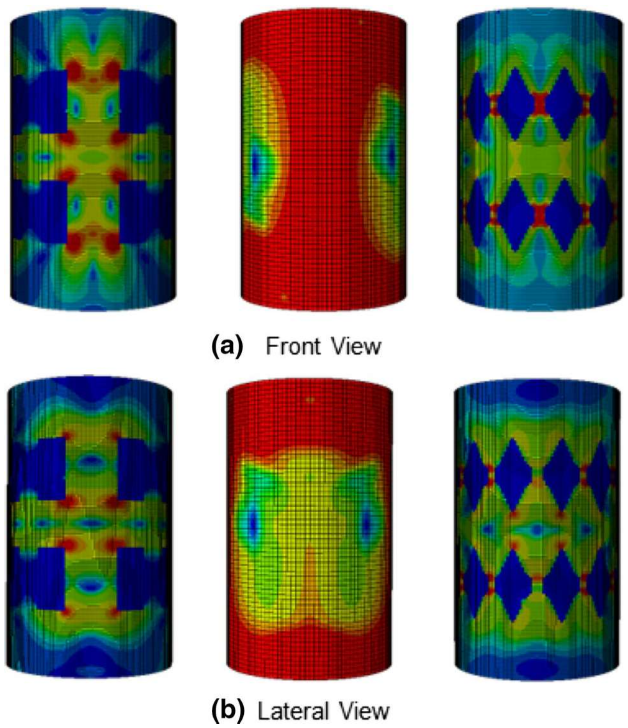

Fig. 4 Illustrative stress distribution: **a** front view and **b** lateral view

question. It is noteworthy that the results shown in Fig. 4 are only illustrative of the mentioned problem.

3 Simulated annealing algorithm

Simulated annealing (SA) is a heuristic optimization technique that follows an analogy with the annealing process in metals, developed in 1983 by Kirkpatrick et al. [31]. Manufacturing an imperfect-free solid implies slow cooling after the material is heated to a high temperature. The SA algorithm randomly generates a new solution from a current iteration and iteratively searches for the optimal solution. In that sense, using random numbers generated from a uniform probability distribution is necessary. The algorithm allows the selection of the current trial solution in a given iteration, even when this solution is worst, mainly at the beginning of the process. This characteristic enables the algorithm to escape local optimums. The acceptance probability (p) of a worst current solution is computed in terms of the objective function for the current and previous iteration (Δf) and the parameter control (T), as given by:

$$p = e^{-\frac{\Delta f}{T}} \tag{1}$$

Suppose the generated solution is better than the previous solution; the current solution is kept. But if the current solution is worst, Eq. (1) is assessed, and the p-value is compared against a uniform random number, nr, between 0 and 1. If nr is higher than p the generated solution continues the process. Otherwise, the previous solution is kept. Then, the temperature value is updated, considering a controlled decrement.

The user must define a criterion that stops the search process. Possible criteria are related to a maximum number of iterations or a pre-specified number of them without a significant improvement in the quality of the solution. The number of iterations has to be defined previously by the user, and it depends on the characteristics of the analyzed problem. Due to the stochastic nature of the algorithm, it is necessary to execute the algorithm several times and then provide the solution to the problem. In addition, the algorithm's success in solving a specific problem depends on the use of heuristics based on the knowledge of the problem, as the SA was derived as a general optimization algorithm. Figure 5 presents the SA pseudocode for its computational implementation, which shows the iterative process in the search for the optimal solution.

The possibility of proposing solution representations according to the problem domain, incorporating problem knowledge-based heuristics, and the ease of its computational implementation turns the SA suitable to be applied to different real problems. For example, SA has proven its value in solving solid mechanics problems. Some applications include structural optimization [32], machines [33], composite materials [34], vibration control [35], bio-engineering [36], structural damage detection [37], mechanical systems [38], sensor placement for dynamic tests [39], model identification parameters [40], among others. Most of the mentioned problems require the evaluation of an objective function based on results from a finite element model, which increments the computation cost. SA presents the advantage of being a single-solution metaheuristic, an essential characteristic for solving problems with an objective function whose computational cost is high.

Fig. 5 Conventional simulated annealing algorithm

Procedure Simulated Annealing Algorithm

Inputs : So, T, k , k_{max}
S_o = Initial Solution
T = Current temperature (control parameter)
k = Number of iterations
Repeat from k to k_{max} Do
begin
Generate a new solution S';
Delta E $\leq$ f (S') - f (S_o) ;
if Delta E $\leq$ 0, S_o = S' ; (current solution is accepted)
else if e ^ (Delta E / T) > random [0,1], S_o = S' ;
else S_o = S_o ;
end
k = k + 1 ;
T = aT ; (control parameter reduction)

4 Methodology for the shape optimization of slotted HCS dampers

The definition of the proposed methodology for the optimization of slotted HCS dampers follows that presented in Ferrer-Fuenmayor and Villalba-Morales [23] for the case of SSP dampers. It is worth mentioning that the optimization process aims to obtain the cylinder shape with the maximum EDC when the user pre-defined material volume. The method introduces four key steps to form the proposed methodology: (1) input data, (2) finite element modeling, (3) application of the simulated annealing, and (4) heuristics. Figure 6 visually describes the interaction between the previous steps, executed from a main computational routine. In this case, the Python language was selected for the computational implementation due to its practical applicability to scientific computing [41]. Furthermore, as proved in this research, the strategy by Ferrer-Fuenmayor and Villalba-Morales [23] can easily be modified to be applied explicitly to different configurations of MH dampers. The main changes carried out in this research are related to the optimization algorithm, the representation scheme for the variables, and the determination of the best solution.

The beginning section refers to the user-provided input data for executing the algorithm. First, it is necessary to define the geometry of the damper's initial configuration, which includes the diameter, height, and thickness of the cylinder and the number, shape, position, and dimensions of the slots. Next, the material description defines the stress–strain relationship and the failure criterion, while the displacement protocol is given in function of the maximum values expected for the devices. Such protocol can be obtained from design codes such as ASCE 7–16 [42]. Then, the parameters that detail the finite element modeling (element type, mesh, analysis type, numerical method) are provided. With that information, it is possible to build a base-finite element model to initiate the optimization process. Then, the SA parameters (number of runs, maximum number of iterations, and cooling temperature) and the variable domain must be given. Finally, the python code implements the solution representation for the optimization algorithm, as shown in Sect. 4.2. It is worth mentioning that the general cylinder dimensions, the material properties, the finite element modeling, and the SA parameters will not change during the optimization process.

The proposed method implies using finite element software that determines the structural response of a specific slotted HCS damper under a cyclic displacement protocol. This research used ABAQUS because it has high numerical capabilities, directly computes EDC, and can be handled from python. It is worth mentioning that the quality of a damper configuration is measured as the energy dissipated under the displacement protocol. The damper finite element model is created from the previous data and numerically solved under the consideration of large deformations. Then, the geometrical configuration of the HCS damper, stress distribution, and energy dissipation are saved. Previous papers on steel damper optimization have used ABAQUS as a finite element tool [17, 26, 43–45].

The SA application implies generating a new solution (new damper configuration) from the neighborhood of the current solution. First, the process creates another