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ADVANCED OPTIMIZATION PROCESSES FOR THE DESIGN OF 3D-PRINTED METAL DAMPERS

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Abstract

Over the past years, the research field concerning the passive seismic protection of buildings gained relevance more and more, due to the severe earthquakes affecting several parts of the world, often hitting very populous areas. Meanwhile, recent additive manufacturing technologies allowed the implementation of innovative metal passive protection devices (dampers), that are ground-breaking both in terms of final geometry and design approaches.
This paper describes an innovative damper typology obtained through the application of additive manufacturing processes and by exploiting advanced topological and geometric optimization algorithms, which are developed within the Abaqus virtual environment. The damper is conceived starting from common geometric shapes, and then designed, through optimization processes, to obtain unconventional shapes, which can be easily obtained through 3D printing processes only, which allow to comply with objective performance in terms of strength, stiffness and dissipative capacity. Moreover, the consequent elimination of parts enables the pursuit of relevant targets, such as material savings, weight and cost reductions. The model threated in this paper, which was obtained by optimizing a spherical shape, was designed to withstand axial stress, simulating the load being transmitted across a diagonal brace of a concentrically braced frame in the event of an earthquake. The performance of the damper proves how the optimization process actually allowed to obtained pre-established and convenient decoupled levels of strength and stiffness.

Keywords: Additive manufacturing, Metal 3D printing, Selective Laser Melting, Seismic dissipation devices, Optimization process, Damper.

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1 INTRODUCTION

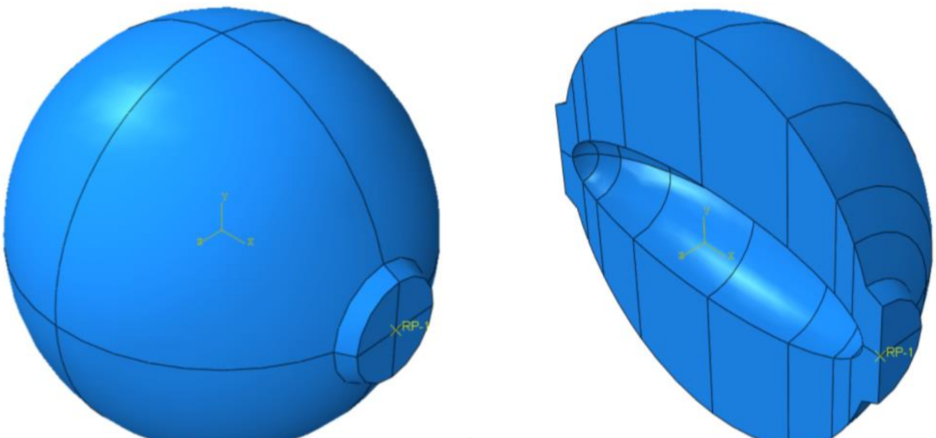
In recent years, seismic risk mitigation has become a topic of great interest for both researchers and experts operating in the field of building engineering. For this reason, nowadays, earthquake engineering plays an increasingly central role in structural design.
Seismic design processes target to achieve a sufficient level of safety, in order to avoid sudden catastrophic collapse of the structure and subsequent loss of life under severe events. A correctly designed building, therefore, must provide for the possibility of evacuation following rare seismic event, reaching an admissible state of damage, but not involving the collapse of structural components [1], [2]. This can be achieved, for example, by introducing additional dissipative elements into the structure, which attract most of the input energy, thus preserving the primary structural members [3], [4]. Several types of supplementary energy dissipation devices have been introduced in literature. These can be classified with respect to the type of mechanism required for activation [5]. In fact, depending on the way they react to earthquake-induced excitation, additional energy dissipation systems can be classified into active and semi-active systems (e.g. Active Bracing Systems, Active Mass Dampers, Variable Stiffness or Damping Systems, Smart Materials) and passive systems (Metallic Dampers, Friction Dampers, Viscoelastic Dampers, Viscous Fluid Dampers, Tuned Mass Dampers, Tuned Liquid Dampers) [3], [6]–[9]. These devices are conceived according to different approaches, depending on how they reduce the effects of earthquakes on structures [2], [4], [10], [11].
In this research area, this paper presents a new type of damper whose shape is achieved by applying advanced optimisation algorithms to a simple geometric starting shapes, namely a sphere. The implementation of optimisation processes allows particularly challenging shapes, to be created through the rationalisation of the simpler geometry by removing portions of material, which allow to achieve pre-established levels of reduced strength, but not modifying the stiffness significantly. This means that the obtained new damper is able to attract, when installed in a frame. the same aliquot of seismic energy but anticipating its dissipative function to low earthquake demands.
3D printing is proposed for production, due to the fact that additive manufacturing allows the production of complex components that would be hard to produce with conventional techniques. Selective Laser Melting, one of the most widely used methods in metal 3D printing, is proposed to this purpose. Through this design process, the desired performance is achieved by decoupling stiffness and strength, so to control them, as target parameters of the optimization process, separately. The aim is therefore to obtain a device that can more efficiently meet the requirements of a structural protection system. The results in terms of force-displacement diagram of the optimisation carried out in the Abaqus environment of a sphere designed to absorb the axial load transmitted by a brace during a seismic action, and the comparison with the starting models are reported.

2 THE PROPOSED MODEL

2.1 The starting shapes

The idea behind the design of the damper was to start with an optimal geometric model withstanding specific design demands in terms of stiffness, also depending on its positioning in the structure. In the current case, a spherical geometry was selected as it is the shape with the ideal best cyclic response, because of its compactness, which is unaffected by buckling phenomena and therefore able to provide ideal dissipative mechanisms. The spherical model was designed to be placed on steel concentrically braced frames (CBF).

The model and the analysis of the damper were implemented within the Finite Element Model software Abaqus. The starting model, shown in Figure 1a, consisted of a spherical geometry with a diameter of 100 mm.
On the end of the sphere two truncated cones constituting the elements that allow the connection, through metallic plates, of the device to the bracing, have been modeled. As for the constraint conditions, an encastre has been applied to the surface of one of the two truncated cones. An axial displacement towards the core of the sphere of 50 mm has been applied, instead, to the opposite end. This displacement was determined by assuming that the damper is installed on the bracing of a single-story frame with dimensions 6000 mm (W) x 3500 mm (H). In order to identify the deformation that the damper have to withstand, the maximum elongation of the entire bracing system (brace + sphere), when the life-safety limit state is reached, was assessed. In the case of CBF, the FEMA Standard recommends calculating the maximum strain of the bracing starting from a limit story drift corresponding to 1.5% of the frame height [12].
This starting model, henceforward referred to as the "full-shape model" (see Figure 1a) was realized with C3D8R elements (8-node general purpose linear brick elements, with reduced integration) with radial mesh distribution from the center of the sphere outwards. To improve the mesh distribution, three partitions were created in the model. One partition is orthogonal to the longitudinal axis of the sphere, while two partitions are parallel to the longitudinal axis of the sphere and mutually perpendicular.
In order to obtain a different material distribution, a second model (Figure 1b), subsequently defined as the "holed model", was developed by subtracting an ellipsoid with dimensions 95 mm (r_1) x 30 mm (r_2) from the starting solid sphere. As can be seen from Figure 1b, it has the same geometric dimensions and modelling features as the full-shape model. However, additional partitions were added.



a) b)

Figure 1: The starting models: a) The full-shape model; b) The holed model.

The material adopted for both models was 17-4 Precipitation Hardening stainless steel (AISI 630). The mechanical parameters were derived from the technical data sheet of the powder material the additively manufactured dampers will be made of, provided by the manufacturer [13]. The constitutive model of the material, implemented in the FEM software, was a trilinear true stress-strain relationship with softening.
Cyclic analyses were conducted on the models. The analyses were performed considering a cyclic loading history with constant amplitude, applying a maximum displacement of 50 mm,

in accordance with the ECCS loading protocol. The analysis in the cyclic field was carried out by applying a quasi-static force with displacement control.
The cyclic loading protocol adopted was selected according to the ECCS standards for structural steel components ("Recommended Testing Procedure for Assessing the Behaviour of Structural Steel Elements under Cyclic Loads", Publication 045 – 1986) [14], in which the key parameter for defining the cyclic loading is the yield displacement d_y, obtained from monotonic tests.

2.2 Optimization processes

Starting with the two preliminary models, various optimization processes were carried out by implementing the Abaqus software optimization module ATOM (Abaqus Topology Optimization Module). The aim of the performed optimization process is to design a structural element with a low pre-established strength but with a stiffness as close as possible to the one of the original shape, so to ensure that the seismic forces are attracted appropriately and significantly by the device.
The process starts with a conventional geometric shape, a solid sphere. The shape of the initial element was selected according to its position within the structure, i.e. on the bracing, and consequently the stress it will be exposed to. The initial stiffness, which can be easily determined by modifying the diameter of the starting geometry, can be established beforehand in accordance with the targets imposed by the service limit states or the rate of seismic force that the damper must attract in the elastic field.
The subsequent step, from a theoretical point of view, is the topological and geometrical optimization of the solids. This process, through the removal of material in excess of the actual structural purposes, ensures that the optimized model provides:
- stiffness similar to the starting solid;
- strength properly reduced to ensure compliance with the targeted activation of the damper dissipative function;
- ductility capacity for accommodating the request of inelastic deformation.

The activation of the dissipative capacity of the damper is managed by reducing the strength of the device to the pre-established design levels, without significantly reducing the original stiffness. The decoupling of strength and stiffness is possible thanks to the shape effect obtained downstream the application of the optimization method, which allows the two parameters to be controlled independently. Figure 2 conceptually shows how the optimization process should bring from the curve of the original shape (the grey curve) to the curve (bolded black) of the optimized damper. This transformation can be carried out by controlling a series of parameters: the objective functions, the constraints and eventual geometric restrictions.
The shapes resulting from the optimization processes will have unconventional and extremely challenging geometries that are not easily realized by conventional manufacturing processes. As a result, additive manufacturing can be considered as an alternative approach that works with design and geometry rather than material.

2.3 The optimized model

From the results of several preliminary optimization attempts, one model was considered particularly successful. This model was obtained by considering as initial model the hollow sphere and by imposing, as main objective functions, the halving of the strength and the maximization of the strain energy, so to maximize the stiffness of the damper. Moreover, some constraints concerning the parts of the initial model to be preserved in the optimization process, defined as frozen areas, have been imposed.

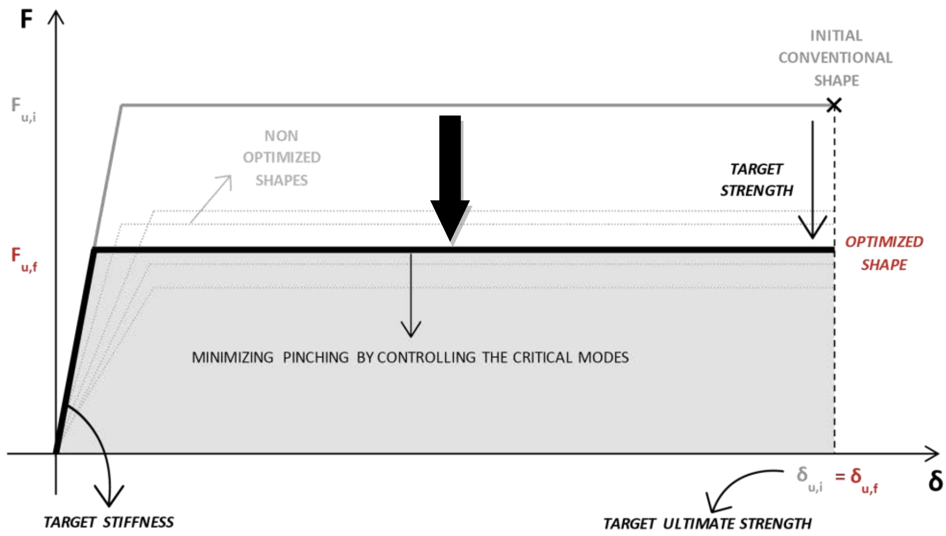


Figure 2: The result of the optimization process.

In particular, 12 outer sectors on the external surface have been constrained to remain after the optimization process, so to assure that the optimized damper has some external parts that undergo plastic mechanisms in bending for very low displacement demands.

In order to better distribute the meshes, the initial model addressed for optimization has been subjected to radial partitions with a relative angle of 15°, this enabling greater manageability of the regions to be frozen. The sphere was therefore divided into 24 sectors. An additional partition orthogonal to the longitudinal axis of the sphere allowed the frozen areas to be thickened.

The geometry of the optimized damper, which was subjected to a subsequent revision, is shown in Figure 3. The revision process consisted in adding to the central core three transverse ribs and eight longitudinal ribs to strengthen the most stressed central section with respect to possible buckling phenomena, which have been controlled through several preliminary buckling analyses that allowed to achieve the final solution. Also, support elements at the two ends of the internal hollow core have been added to avoid manufacturing problems caused by excessive overhang angles.

The same constraint conditions of the two starting models were also maintained on this model, i.e. an encastre on one of the two ends and the same displacement history (maximum amplitude of 50 mm) on the opposite end.

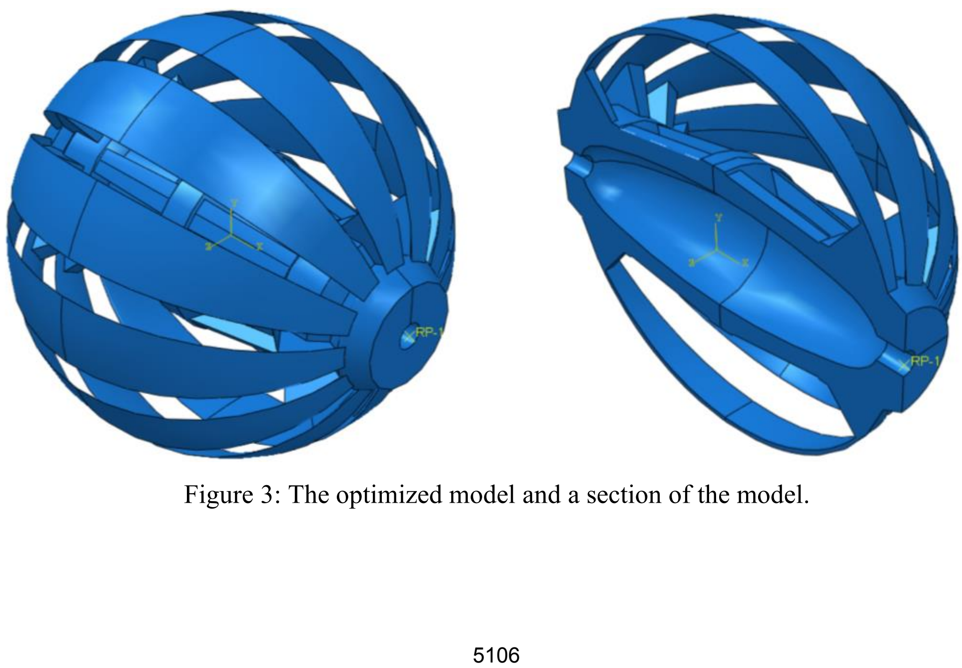


Figure 3: The optimized model and a section of the model.

The numerical model consisted of 10-node tetrahedral configuration 3D elements, defined in Abaqus software as C3D10 elements (general purpose tetrahedral element with 4 integration points).

3 RESULTS AND REMARKS

The results of the numerical tests performed on the three models are shown in Figure 4, in terms of force-displacement cyclic curves. As it is possible to observe, the objective of the optimization process was successfully achieved. In fact, the optimized damper present a strength of about 360 kN versus the strength of about 720 kN provided by the hollow sphere considered as initial shape. Also, the optimized damper presents the same stiffness of both the holed model and the full shape, as it is possible to observe by comparing the unloading branches of the cycles. Finally, it must be pointed out that the optimized damper features full cycles that are not affected by pinching phenomena, this meaning that the addition of ribs in the inner core allowed to avoid buckling phenomena which would have provoked undesired detrimental effects.

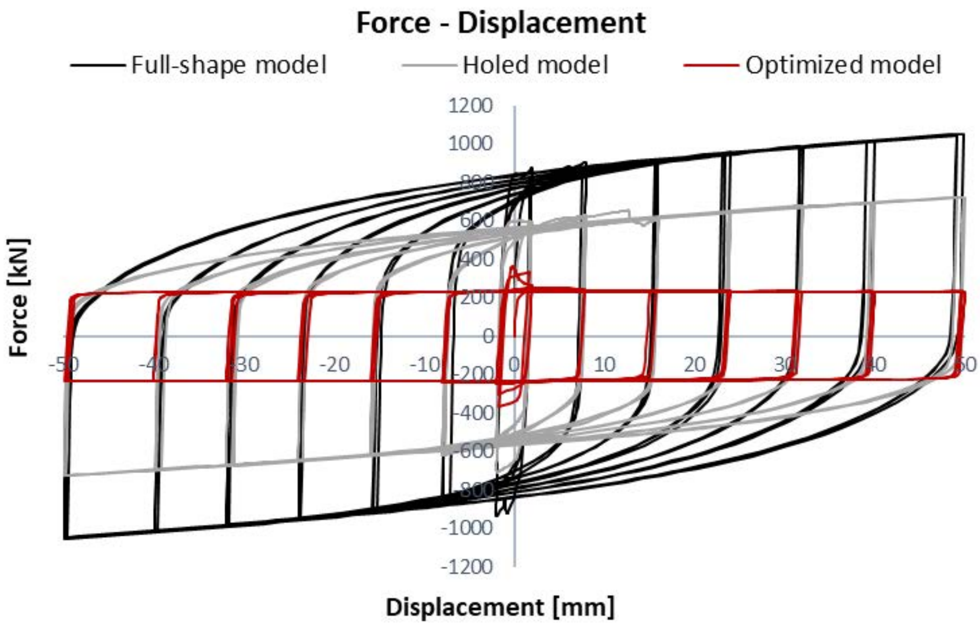


Figure 4: Results of the numerical tests.

The optimized damper features a weight of 6.13 kg versus 41.4 kg (saving of material equal to 85%) and 37.9 kg (saving of material equal to 77%) of the full and the hollow shapes respectively.

4 CONCLUSIONS

In this paper a new metallic damper has been presented. It has been conceived by exploiting the potentialities of some optimization algorithms that allowed to transform a conventional shape, a sphere, so to decouple the strength and the stiffness once that it is subjected to axial force. Both the optimization process and the cyclic non linear analyses have been developed through the FEM software Abaqus.

Based on the cyclic tests performed on the starting models and the final optimized damper, the following conclusions can be given:

- The optimized damper presents a good dissipative behavior, with full cycles, that are not affected by pinching phenomena, and a high ductility.
- The objective of the optimization process concerning the halving of strength with respect to the original shape have been successfully achieved.
- Also, the optimized damper guaranteed a stiffness that is very close to the one provided by the original shape and this is a not trivial achievement, considering the reduction of strength, that is completely due to the new shape obtained downstream the application of the optimization process.
- The new shape featured a weight that allowed the 85% of saving of material.

The new damper, perfectly match one of the main targets of the design processes to be implemented for the passive protection of buildings through special devices: providing supplemental damping through dampers characterized by a low strength, so to activate their dissipative function already for low demands, but characterized by a high stiffness, which allows to attract toward the dampers themselves the seismic actions, so to preserve from damage the other primary elements of the structure. In the case being, the stiffness of the optimized damper is very closed to the one of the original shape that, moreover, represents a design parameter that can be easily managed.
The new shape of the optimized damper is for sure one of the challenging issues to be e faced, but as it was widely discussed in the paper, it can be easily threated by recurring to the modern additive manufacturing process.

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