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OPTIMIZATION OF ADDITIVELY MANUFACTURED METAL DAMPERS

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Abstract. This paper presents a novel typology of metallic energy dissipation device (damper) for seismic protection of buildings, distinguished by its capacity to independently modulate strength and stiffness parameters. This objective is accomplished through the implementation of non-standard geometries, enabled by advanced additive manufacturing techniques and informed by topological optimization methodologies. These methods are applied to conventional baseline geometries, chosen to preserve a pre-determined stiffness level. The optimization process strategically reduces the yielding strength of the original configuration without compromising its initial stiffness, allowing the damper to engage its energy dissipation function under low seismic demand. At the same time, the maintained high stiffness ensures the capacity of the damper of attracting seismic forces when is integrated into structural frames during earthquake events. Two type of devices are proposed: they are engineered to operate under axial and torsional loading conditions and are derived from spherical and cylindrical baseline geometries, respectively. Numerical models are developed in ABAQUS environment, where, by applying topological and geometrical optimization algorithms, the yielding strength is reduced by 50% while preserving the original stiffness characteristics. The results confirm that the optimized dampers, for both investigated geometries, meet the design targets in terms of strength and stiffness, highlighting their potential effectiveness in seismic energy dissipation.

1 INTRODUCTION

Seismic risk mitigation has become a key focus for researchers and technicians operating in structural engineering. As a result, earthquake engineering has gained recently a more prominent role in structural design. As it is well known, modern seismic design methodologies aim to ensure sufficient safety standards to prevent catastrophic structural failure and the associated loss of life. Properly designed buildings must enable safe evacuation following seismic events while ensuring that damage remains within acceptable limits, thereby preventing the failure of critical structural components ([1], [2]). One of the most effective strategies involves integrating supplementary dissipative devices into structures, so to absorb through them the majority of incoming energy, thereby safeguarding primary structural components. ([3], [4]).

Literature reports diverse types supplementary energy dissipation devices, which can be categorized based on their activation mechanisms [5]. Depending on their response to seismic excitation, these additional energy dissipation systems are classified as either active/semi-active systems (Active Bracing Systems, Active Mass Dampers, Variable Stiffness or Damping Systems, Smart Materials) or passive systems (Metallic Dampers, Friction Dampers, Viscoelastic Dampers, Viscous Fluid Dampers, Tuned Mass Dampers, Tuned Liquid Dampers) ([4]-[11]). These devices employ distinct techniques to mitigate earthquake impacts on buildings ([12], [13]).

Within this research framework, this paper presents a novel approach for designing seismic dissipative devices using advanced optimization algorithms to transform simple geometric shapes into tailored shapes. By selectively removing excess material, the design achieves reduced strength while preserving the original stiffness. This results in dampers that, when integrated into structural frames, effectively absorb seismic energy and activate their energy-dissipation capabilities at lower seismic demand levels, even though their capacity of attracting seismic force remain unaltered. Additive manufacturing was chosen over traditional methods to produce these complex components, with Selective Laser Melting, a leading metal 3D printing technique, selected for production [14].

By decoupling stiffness and strength, the design process aims to optimize the performance of the structural protection system, independently controlling these parameters as distinct optimization targets. This study presents the optimization results applied to spherical and cylindrical base shapes, generated using Abaqus CAE Finite Element Software [15]. The sphere was conceived to absorb axial loads transmitted by a brace, whereas the cylinder was thought to absorb torsional loads transmitted by a beam-to-column node during seismic activity.

2 THE OPTIMIZATION PROCEDURE

Multiple optimization iterations were performed utilizing the Abaqus Topology Optimization Module (ATOM). The primary objective of this optimization methodology was to engineer a structural component exhibiting predetermined lower strength while preserving stiffness characteristics nearly identical to those of the original model. This design approach ensure that the optimized element effectively attracts and withstands seismic loads, maintaining the desired load path through the structure, while enhancing energy dissipation capabilities at lower force thresholds.

The optimization procedure starts using a conventional shape as the initial geometric configuration. The selection of specific shape must be strategically determined based on the positioning of the damper within the structure. The initial stiffness of the device, which can be readily calibrated through dimensional adjustments (e.g. the diameter, the length, etc.), is established in accordance with the performance specifications imposed by the service limit states and the targeted rate of seismic force the device must effectively attract while operating within the elastic range.

From a theoretical standpoint, the subsequent phase involves the topological and geometrical optimization of the solids. This process entails the strategic removal of redundant material beyond what is structurally essential, guided by advanced computational algorithms. The resulting optimized configuration maintains stiffness comparable to that of the starting shape while appropriately reducing strength to achieve the targeted activation threshold for the energy dissipation functionality of the device.

The regulation of the energy dissipation capabilities of the damper involves the strategic reduction of the strength to pre-established design levels while preserving its original stiffness. This critical decoupling of strength and stiffness is achieved through the shape effect generated by the optimization methodologies, which permits independent control of these two key mechanical properties. Figure 1 provides a conceptual representation of the optimization procedure, illustrating the transition from the initial configuration (depicted by the thin black curve) to the optimized geometry (represented by the thick black curve). This transformation can be precisely controlled through the manipulation of multiple parameters, including objective functions, constraint conditions, and geometric restrictions within the optimization framework.

The geometries resulting from these optimization processes exhibit unconventional and intricate configurations that exceed the fabrication capabilities of conventional manufacturing methodologies. Consequently, additive manufacturing emerges as an alternative production approach that emphasizes design freedom and geometric complexity.

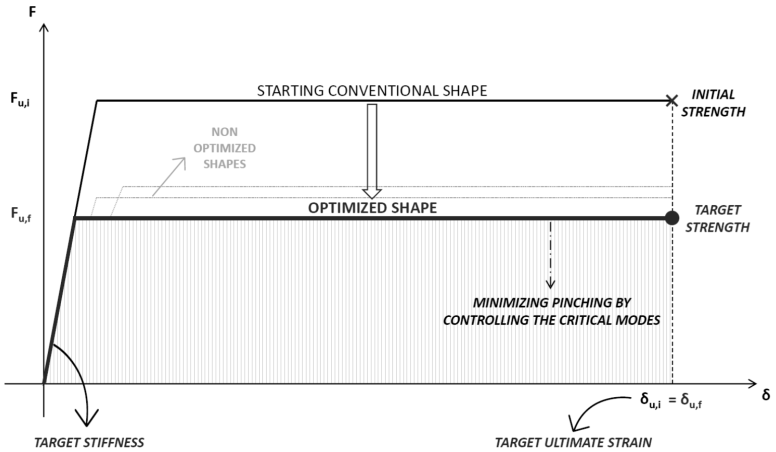

Figure 1: Schematic representation of the optimization procedure

3 3D-PRINTED DAMPERS: THE STUDIED SHAPES

3.1 General

The design of the devices was based on the concept of determining optimal geometric models capable of withstanding specific design requirements in terms of stiffness, particularly in relation to the dampers position within the structural system. To achieve this objective, both spherical and cylindrical shapes were investigated. These two geometries demonstrated the most favorable response to cyclic loads in the current application, due to their compact nature which effectively resists buckling phenomena, thus enabling ideal dissipative mechanisms.

The models of the devices and numerical analyses were implemented within the Finite Element Modelling software Abaqus CAE. The material selected for the numerical modelling was 17-4 Precipitation Hardening stainless steel. The mechanical properties of this material were established following the comprehensive experimental campaign detailed in a previous study by the authors ([15]-[17]). The material behavior in the FEM software was represented through a trilinear true stress-true strain constitutive relationship with softening branch.

The models were subjected to cyclic analyses. These analyses were conducted by applying a cyclic loading history (displacement for the sphere and rotational displacement for the cylinder) with progressively increasing amplitude. This methodology adhered to the protocols recommended by the European Convention for Constructional Steelwork (ECCS) standards for structural steel components [18].

3.2 The sphere

The spherical model was specifically conceived for being integrated within the bracing system of concentrically braced steel frames (CBF). The initial prototype, illustrated in Figure 2, featured a spherical geometry with a 400 mm diameter, characterized by a central hole obtained removing an ellipsoid with dimensions of 380 mm (r_1) x 120 mm (r_2) from the solid. The sphere incorporated two truncated cones at the two opposite ends, which functioned as connection elements between the device and the bracing by means of metallic plates. To establish appropriate boundary conditions for the analysis, one truncated cone was fixed, while an axial displacement of 50 mm directed toward the center of the sphere was applied to the opposite end.

The starting model developed in Abaqus was discretized using C3D8R finite elements (8-node general purpose linear brick elements with reduced integration), with a mesh arranged in a radial pattern extending from the center of the sphere to the exterior.

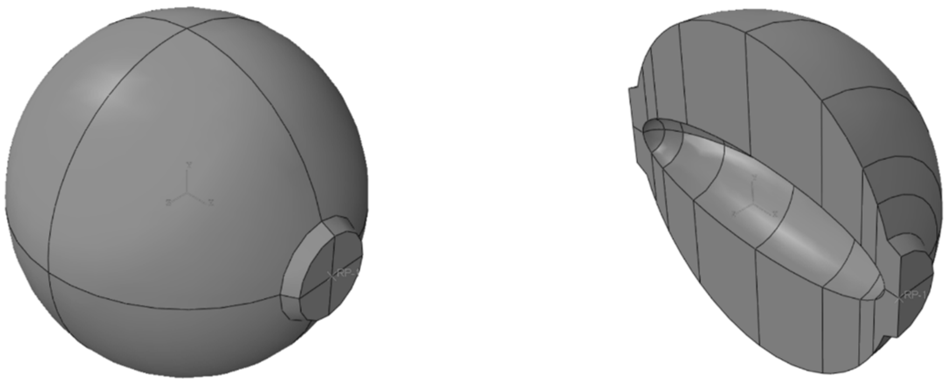

Figure 2: The spherical starting model

Following multiple preliminary optimization iterations, one model demonstrated good performance. The optimization process employed an objective function that minimized strain energy, with the specific aim of maximizing the stiffness of the damper.

To preserve critical regions during the optimization process, specific constraints, designated as frozen areas, were established. Specifically, 12 external sectors on the outer surface were excluded from the optimization process to prevent their removal during, thereby ensuring that the optimized configuration would maintain external portions capable of developing plastic bending mechanisms at low displacement levels.

The geometry of the optimized damper, which underwent subsequent refinement, is illustrated in Figure 3. The obtained shape was finally slightly adjusted by strengthening the central core with three transverse ribs and eight longitudinal ribs to reinforce the highly stressed central section against potential buckling phenomena. These modifications were implemented following preliminary buckling analyses that guided the development of the final configuration. Additionally, support elements were incorporated at both ends of the internal hollow core to mitigate manufacturing challenges associated with excessive overhang angles.

The boundary conditions applied to the initial model were maintained for this optimized configuration. These conditions comprised a fixed support on one end and the application of an identical displacement cyclic history (maximum amplitude of 50 mm) on the opposite end.

This model was meshed with 10-node tetrahedral configuration 3D elements, defined in Abaqus software as C3D10 elements (general purpose tetrahedral element with 4 integration points).

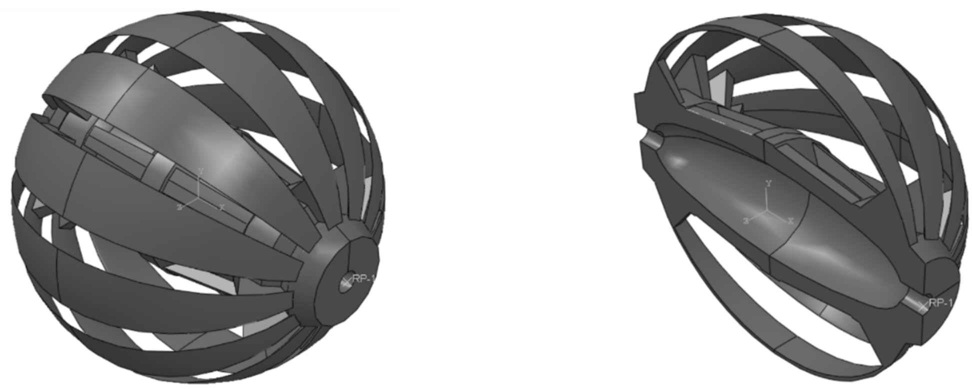

Figure 3: The spherical optimized model

3.3 The cylinder

The cylindrical model was designed for installation at beam-to-column nodal connections within a frame. Its primary function is to withstand uniform torsional stresses that develop at these critical points. The initial model consisted of a solid cylinder with both diameter and length measuring 260 mm (Figure 4). Boundary conditions were implemented with one outer face fixed (encastre), while the opposite face was subjected to a rotational displacement of 0.12 rad around the longitudinal axis of the cylinder.

The starting model implemented in Abaqus was discretized using C3D8R finite elements (8-node general purpose linear brick elements with reduced integration).

Based on the results of several preliminary optimization iterations, one model demonstrated superior performance. This model was developed establishing the maximization of eigenfrequencies as the objective function, with the specific aim of enhancing the stiffness of the damper. The geometry of the optimized damper is illustrated in Figure 5.

Additionally, the boundary conditions applied to the initial model were maintained for this optimized configuration. These conditions comprised an encastre (fixed support) on one end, though in this case, only the external circular ring was fixed to facilitate the optimization procedure, and the application of an identical rotational displacement history, with maximum amplitude of 0.12 rad, on the opposite end. Also this model was created with solid 8-node general purpose linear brick elements with reduced integration, defined in Abaqus software as C3D8R finite elements.

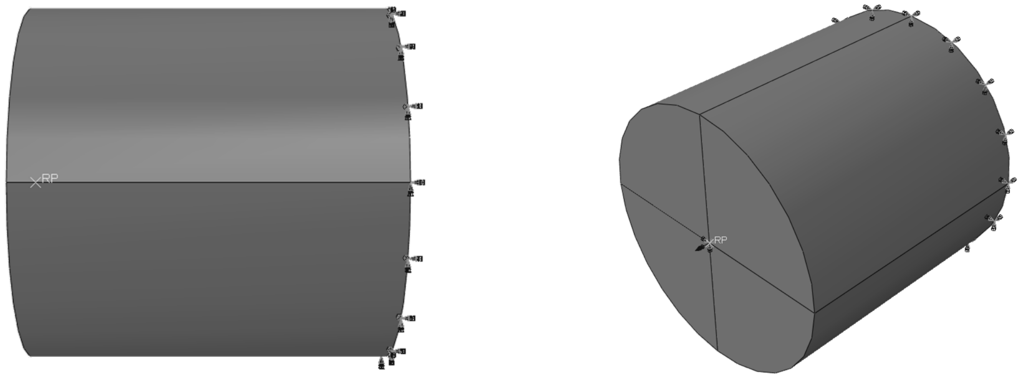

Figure 4: The cylindrical starting model

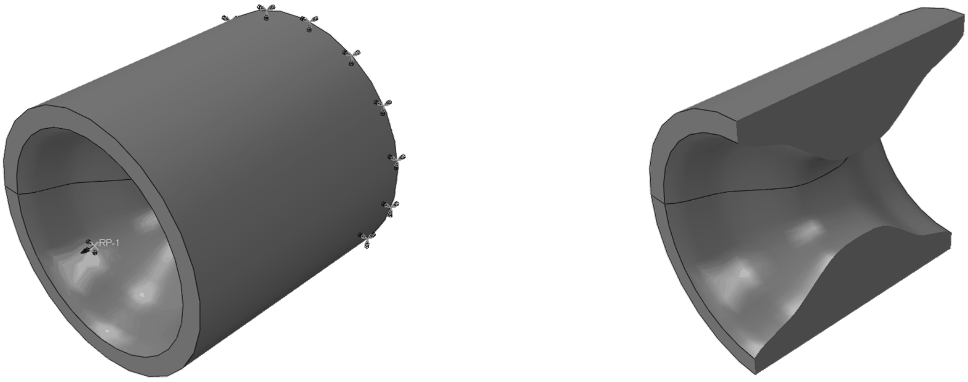

Figure 5: The cylindrical optimized model

4 RESULTS

4.1 The spherical model

The results of the numerical analyses performed on the models are presented in Figure 6, which displays the force–displacement hysteretic curves. The findings clearly demonstrate that the optimization process successfully met its design objectives. Specifically, the optimized damper achieves a peak strength of approximately 3650 kN, significantly reduced from 9580 kN in the original configuration. Despite this reduction, the optimized device retains nearly the same stiffness as the initial model, as evidenced by the comparable unloading branches of the hysteresis cycles. Furthermore, the optimized damper exhibits stable, full hysteretic cycles without signs of pinching, indicating that the incorporation of internal reinforcing ribs effectively suppressed local buckling, which could have otherwise compromised performance. Remarkably, the mass of the optimized damper is only 40 kg—an 84% reduction compared to the original 247 kg configuration.).

4.2 The cylindrical model

Figure 7 presents the global cyclic response of the two cylindrical models in terms of moment–rotational displacement relationships. Also in this case, the comparison between the baseline and optimized configurations confirms that the primary objective of the optimization process was successfully achieved. The optimized cylinder attained a peak moment capacity of approximately 830 kNm, representing a significant reduction from the 1650 kNm exhibited by the original solid cylinder.

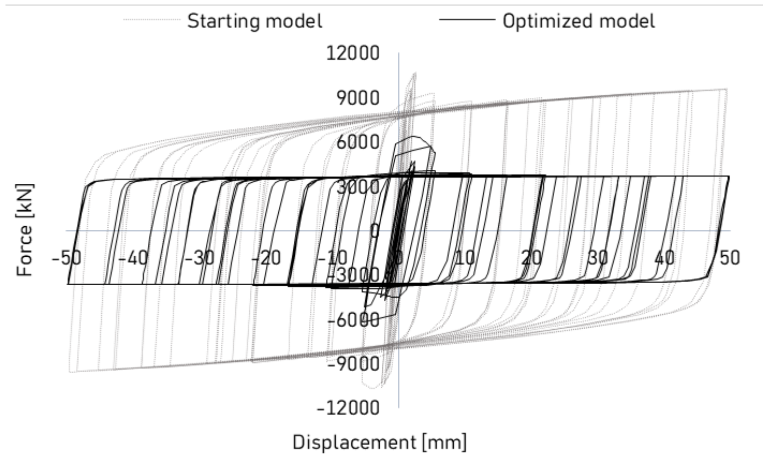

Figure 6: Comparison of cyclic behaviour between the starting model and the optimized model for the spherical shape

Moreover, the optimized damper retained stiffness comparable to the initial model, as indicated by the similarity of the unloading branches in the hysteretic curves shown in Figure 7. Notably, the optimized configuration exhibited full hysteretic cycles without signs of pinching, highlighting the stability of its energy dissipation behavior. Additionally, the optimized damper achieved a mass of 71 kg, representing a 35% reduction compared to the 110 kg of the original configuration.

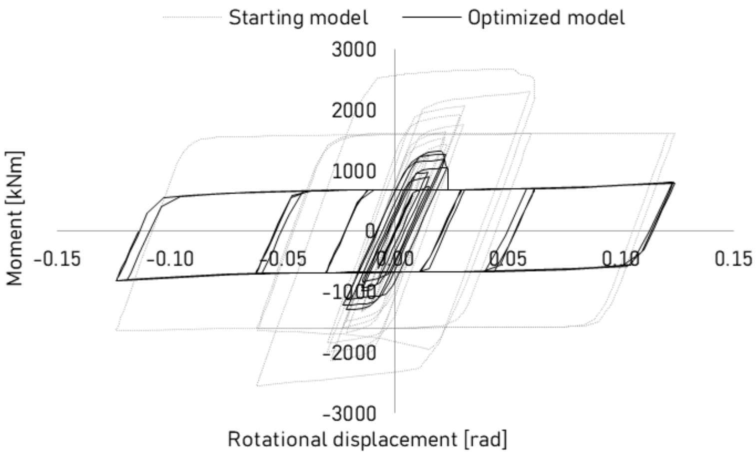

Figure 7: Comparison of cyclic behaviour between the starting model and the optimized model for the cylindrical shape

5 CONCLUSIONS

This paper introduced a novel metal damper typology, developed through computational optimization algorithms that transform conventional geometries into devices with equivalent stiffness but substantially reduced strength. The resulting non-standard shapes are particularly well-suited for fabrication via additive manufacturing. Both the optimization and the nonlinear cyclic analyses were performed using the finite element software Abaqus.

The initial baseline geometries considered in this study are a sphere and a cylinder. Based on the cyclic tests conducted on both models and the comparison between the original and optimized configurations, the following general observations were derived:

- The optimized dampers effectively dissipated energy, exhibiting stable hysteretic cycles free from pinching and demonstrating high ductility.
- The optimization goal of reducing strength to approximately half of the original configuration was successfully achieved.
- Remarkably, the optimized dampers maintained their stiffness comparable to the original design, despite the strength reduction being solely due to the geometric modifications introduced by the optimization process.
- Both optimized geometries led to substantial material savings, with the spherical configuration achieving an 85% weight reduction and the cylindrical configuration a 35% reduction.

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