

Integrating Topology Optimization and Lattice Infilling for Lightweight Aircraft Bracket Design via Additive Manufacturing

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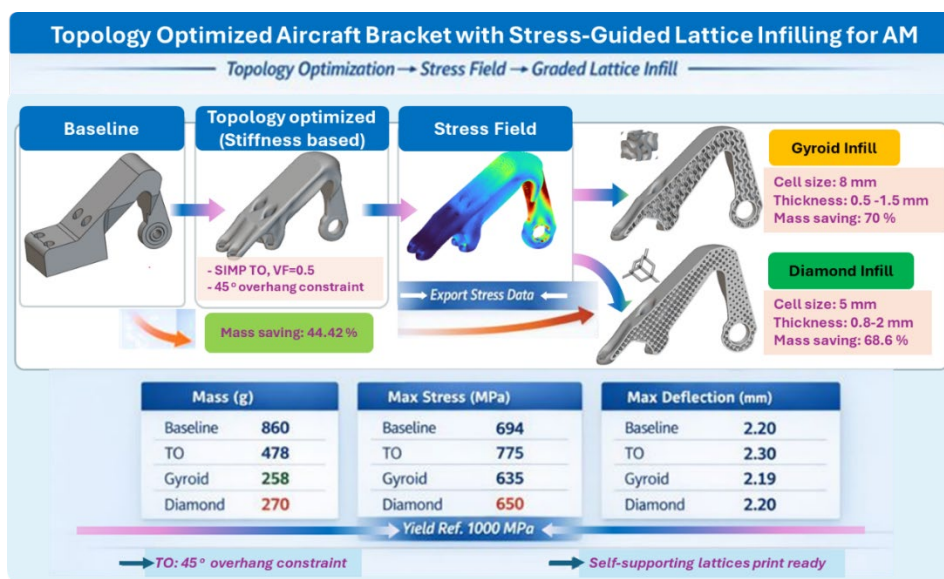
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Abstract. Integrating topology optimization (TO) with lattice infilling for additive manufacturing provides an effective route to lightweight, high-performance structures for aerospace applications. Reducing structural mass can deliver environmental and economic benefits by lowering fuel consumption and associated emissions. This study evaluates a computational workflow for weight reduction of an aircraft bearing bracket by combining topology optimization with stress guided lattice infilling. First, compliance minimizing TO is performed under additive manufacturing constraints to obtain an efficient global load-path layout. Next, lattice infill is introduced using both Triply Periodic Minimal Surface (TPMS) unit cells (gyroid) and strut-based unit cells (diamond). To avoid manual trial-and-error in selecting unit cell size, and thickness, an implicit modeling approach with Python-driven iteration is used to systematically explore lattice parameters and identify feasible configurations. The proposed method uses the TO-derived stress field to tailor lattice parameters spatially, enabling graded cellular architectures aligned with local load demands. Compared with the baseline bracket, TO alone achieved a 44.42% mass reduction, while the stress-guided lattice designs achieved 70% (gyroid) and 68.6% (diamond) weight savings. Finite element analysis is used to compare the baseline, TO, and lattice-infilled brackets in terms of mass, maximum deflection, and von Mises stress, demonstrating that stress-guided lattice infill can improve structural efficiency beyond TO alone while maintaining AM oriented manufacturability through self-supporting cellular features. A key contribution is an automated, stress-guided ramp mapping for graded lattice-parameter control, which is broadly applicable to other components, loading scenarios, and lattice families.

Graphical Abstract



1 Introduction

Additive manufacturing (AM) has emerged as a deriving force in modern manufacturing, transcending its origins in rapid prototyping to enable the production of end-use structural components across industries such as aerospace, automotive, and biomedical [1]. This shift is driven by AM's unparalleled design freedom, which allows for the fabrication of complex geometries that are unattainable through conventional methods. In aerospace applications, where lightweighting is critical to reducing fuel consumption and CO₂ emissions, AM synergizes with advanced design strategies like topology optimization and lattice structures to achieve optimal mass reduction without compromising structural integrity. Topology optimization mathematically redistributes material within a design space to meet performance criteria under specified loads and constraints. Over decades, TO methodologies have evolved, including homogenization [2], evolutionary structural optimization (ESO) [3-5], level-set methods [6], and the widely adopted Solid Isotropic Material with Penalization (SIMP) [7, 8]. SIMP assigns a pseudo-density variable to each finite element, penalizing intermediate densities to steer designs toward binary (solid/void) solutions. Its computational efficiency has enabled landmark applications, such as a 64% mass reduction in Airbus A320 hinge brackets [9] and a 41.25% weight saving in RUAG's Sentinel satellite brackets [10]. Despite these successes, TO-generated designs often exhibit intricate geometries that challenge traditional manufacturing, underscoring AM's role in realizing such optimizations. Complementing TO, lattice structures offer a lightweighting alternative by replacing solid volumes with porous, repeating unit cells [11]. These structures excel in conditions requiring high strength-to-weight ratios, energy absorption, and thermal management [12, 13]. Among lattice architectures, TPMS designs such as the gyroid, and strut-based lattices such as the diamond, have gained prominence due to their biomimetic geometries, tunable stiffness, and self-supporting printability [14-16]. Comparative study by Al-Ketan et al. [17, 18] reveal that sheet-type lattices may outperform strut-based designs in compressive strength, attributed to their continuous, curvature-driven load transfer. Furthermore, the design of graded lattices enables spatially tailored mechanical responses, enhancing performance under applied loading [5, 19-21].

However, critical gaps remain in understanding the parameters that affect the mechanical properties of these lattice structures, which are vital for aerospace applications. While Alsalla et al. [22] reported orientation dependent fracture toughness in 316L gyroid lattices, and limited studies explore TPMS [23] and honeycomb [24] architectures, comprehensive data remain scarce. This is compounded by the suboptimal performance of uniform lattices compared to TO-driven designs [13], prompting interest in hybrid approaches that integrate TO with lattice infills. Such synergies aim to enhance mechanical efficiency, reduce support structures, and mitigate deformation [25]. For instance, embedding lattices within TO-optimized shells could balance global stiffness with local energy absorption. Yet, most research focuses on canonical problems (cantilever beams [11, 26]), leaving real-world industrial applications underexplored.

The core innovation of this work lies in its hybrid methodology, which integrates topology optimization with tailored lattice infill strategies to maximize weight reduction in aerospace components while adhering to additive manufacturing constraints. This integrated framework facilitates a systematic evaluation of trade-offs and benefits across diverse lightweight design approaches. Initially, traditional SIMP-based topology optimization was performed on an aerospace bracket, and resulting stress field from topology optimized structural FEA was used to guide the lattice infill process using nTop tool [27]. The stress map served as a path for selectively infilling the topology optimized structure with lattice architectures for additional weight savings. Python-based script was developed to automate the variation of lattice parameters, such as unit cell size and thickness, based on the stress distribution. To identify feasible configurations, the mechanical response of lattice infilled structures was rigorously analysed through structural FEA. The resulting hybrid designs were then evaluated against key performance metrics, including static mechanical behaviour, mass efficiency, support structure requirements, and overall manufacturability. The preceding Section 2 presents the integrated framework that combines topology optimization with lattice-parameter tailoring, along with the material specifications and finite element simulation

procedures. Section 3 assesses the weight savings and mechanical performance of the original, topology-optimized, and lattice-infilled brackets through comparative displacement and stress analyses. Finally, the conclusion summarizes the key findings and discusses their implications for spacecraft applications.

2 Materials and Methods

2.1 Case Study

The case study is based on the GrabCAD Alcoa airplane bearing bracket challenge [28], which aimed to minimize bracket mass within a fixed design envelope while satisfying FEA-verified performance requirements and reducing the need for additive manufacturing support structures. The component studied is an additively manufactured aircraft bearing bracket constrained to this prescribed envelope and bolted to a high-stiffness mating plate using four #10-32 high-strength bolts (Fig. 1). The bracket is statically loaded through a stiff spherical bearing of 7.94 mm diameter, using load case of 5.56 kN horizontal. The specified material is 15-5PH stainless steel (AMS5862), modeled as linear elastic with $E = 200$ GPa, $\nu = 0.27$, yield strength = 1000 MPa, and density = 7833 kg/m³.

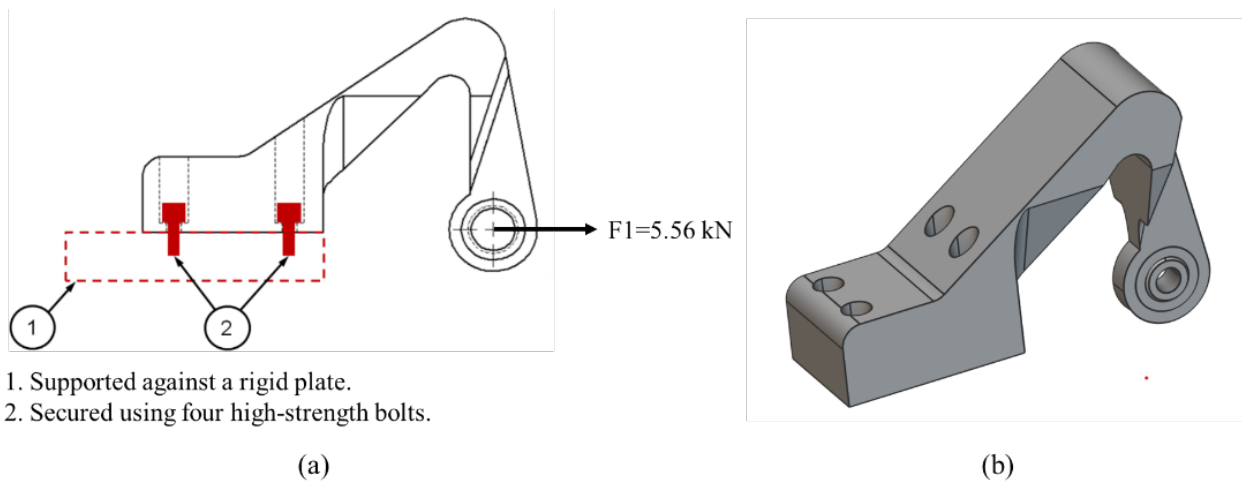


Fig. 1. Baseline airplane bearing bracket and setup: (a) Schematic showing the bolted support region on a stiff plate and the applied load at the bearing interface, (b) 3D CAD model of reference bracket geometry.

2.2 Integrated TO-Lattice Design Framework

The proposed framework integrates topology optimization with lattice parameter tuning to achieve structurally efficient and lightweight designs as shown in Fig. 2a. Initially, a solid part undergoes topology optimization to determine the optimal material distribution under the applied load. Compliance minimization was used as the objective function with a prescribed volume fraction of 0.5, while incorporating an additive manufacturing constraint that limits the maximum overhang angle to 45°. The TO generated geometry is evaluated under applied loading conditions where the von mises stress field is exported as field to tailor lattice parameters such as unit cell thickness, and cell size. This variation is implemented using a ramp function that maps the exported stress field into lattice parameters. The mapping assigns smaller unit cell sizes and larger lattice thicknesses in high stress regions, and larger unit cell sizes with smaller lattice thicknesses in low stress regions. Let $F(x, y, z)$ denote a given stress field. A lower stress bound a_0 and an upper stress bound a_1 are specified, with corresponding thickness limits b_0 (minimum) and b_1 (maximum):

$$F_{\min} = a_0 \Rightarrow t_{\min} = b_0, F_{\max} = a_1 \Rightarrow t_{\max} = b_1 \quad (1)$$

Using these bounds, a mapped field $G(x, y, z)$ is constructed that converts stress values into thickness values. The mapping clamps stresses outside $[a_0, a_1]$ to the thickness limits, and linearly interpolates within the interval:

$$G(x, y, z) = \begin{cases} b_0, & F(x, y, z) \leq a_0, \\ b_1, & F(x, y, z) \geq a_1, \\ b_0 + \frac{F(x, y, z) - a_0}{a_1 - a_0} (b_1 - b_0), & a_0 < F(x, y, z) < a_1 \end{cases} \quad (2)$$

This transformation effectively rescales the original stress field F into a thickness field G , ensuring G varies smoothly between b_0 and b_1 as F transitions from a_0 to a_1 . Within these bounds, linear interpolation provides a continuous gradation of lattice thickness throughout the part, as illustrated in Fig. 2b. A python script based design of experiments approach is employed in nTop tool [27] to design these lattice structures by meeting the global stiffness of the bracket. The objective function focuses on mass minimization, while constraints include allowable deflection limits. This TO-derived stress map ensures that denser lattice regions (areas of higher stress) for structural demand. Conversely, low stress regions are assigned more compliant lattice configurations to reduce weight without compromising performance. The design is refined iteratively by changing lattice parameters until the desired performance criteria are achieved. The resulting lattice structure is then evaluated through numerical simulations to validate its performance under the same applied loading conditions. Due to the geometric complexity of the lattice structure, it was discretized using tetrahedral elements. A mesh convergence study was conducted to determine best element size. A mesh size of 0.4 mm was selected, as further refinement did not significantly affect the results but substantially increased the simulation time. Finite element simulations were carried out in nTop on a dedicated HP Z8 G4 workstation featuring an Intel® Xeon® Platinum 8260M CPU @ 2.40 GHz (24 cores, 48 threads) and 128 GB of RAM. Each simulation required approximately 2 to 3 hours to complete, depending on model complexity.

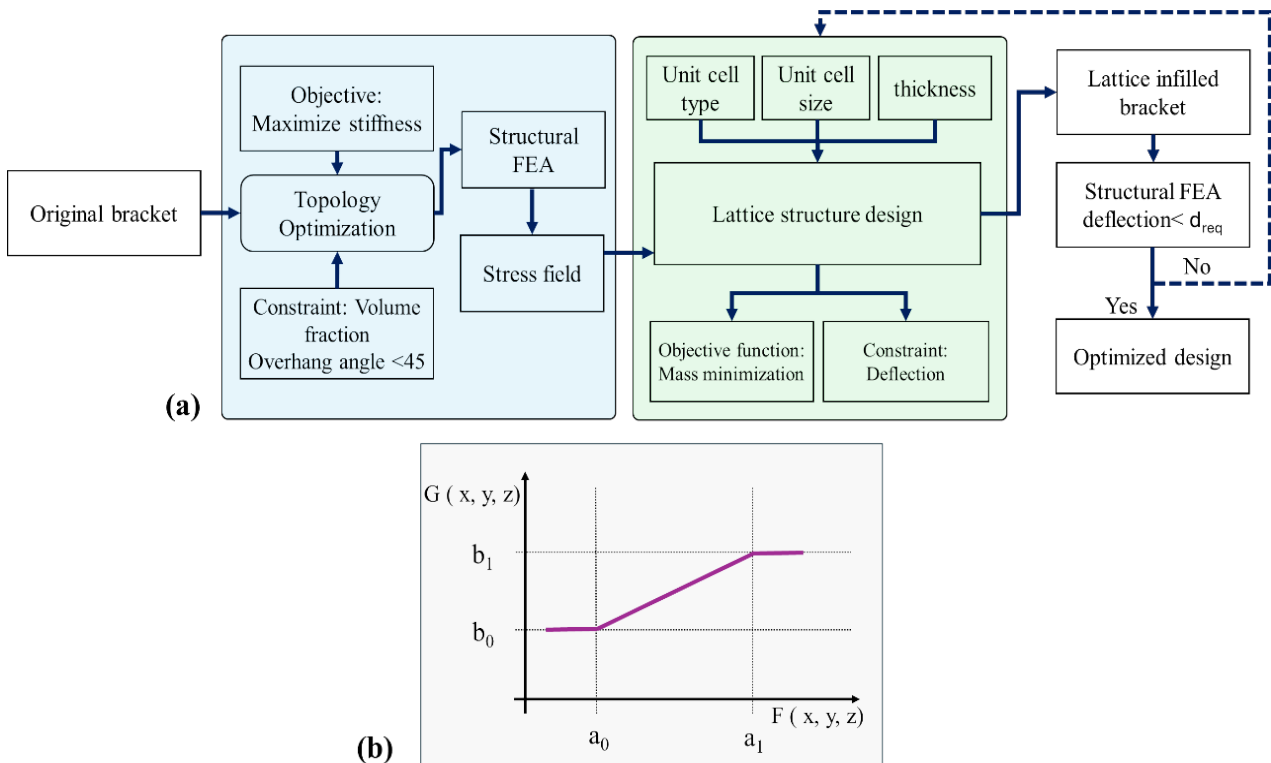


Fig. 2. (a) Integrated framework for topology optimization and lattice parameter tailoring using python-based scripting for lightweight design, (b) Stress-to-lattice parameters ramp function defining $G(x, y, z)$ between b_0 and b_1 over the stress bounds a_0 and a_1 .

3 Results and Discussion

3.1 Weight saving of bracket designs

The lattice configurations that met the design requirements in this study converged to two distinct parameter sets: a gyroid TPMS lattice with an 8 mm unit cell size and a graded thickness of 0.5-1.5 mm, and a diamond strut-based lattice with a 5 mm unit cell size and a graded strut thickness of 0.8-2.0 mm. These feasible bounds provide a practical balance between manufacturability and structural performance by allowing thicker members in highly stressed regions and thinner members where stress is lower. Using these finalized parameters, the mass comparison across all designs shows a clear improvement in lightweighting as illustrated in Fig. 3. The original bracket weighed 860 gm, while topology optimization reduced the mass to 478 gm, corresponding to 44.42% weight saving. Introducing lattice infill on the TO-derived design space delivered a further step change: the gyroid infilled bracket achieved 258 gm (70 % weight saving) and the diamond infilled bracket achieved 270 gm (68.60% weight saving). The small mass difference between the two lattice options (12 gm, around 1.4% of the original mass) indicates that both cellular strategies provide comparable lightweighting potential, with the gyroid offering a modest advantage in this study. This trend is consistent with prior aerospace bracket redesign studies that couple TO with lattice generation to achieve substantial weight reduction while still satisfying loading requirements; for example, William-Sobers et al [29]. reported a 52.5% reduction for an airplane bearing bracket. Furthermore, from a design standpoint, topology optimization provides the macroscopic layout by identifying the critical load paths, while lattice infilling refines the microscopic architecture to achieve fine tuned performance [2, 30]. The TO stage primarily ensures global stiffness and structural continuity; importantly, it is carried out with an additive manufacturing overhang constraint to limit unsupported features and thereby minimize the need for support structures during fabrication [31]. Building on this, the lattice infilled designs introduce local tunability and improved manufacturability, since the selected lattice architectures are inherently self-supporting over practical build orientations, further reducing support requirements within internal volumes [32].

This integrated strategy offers substantial advantages for additive manufacturing. Both TO and lattice infilling generate organic, free-form geometries that align well with AM design freedom, but the inclusion of manufacturing aware constraints at the TO level and self-supporting cellular infill at the lattice level directly improves print feasibility. In addition, lattice parameters are spatially tailored to manage stress distribution and stiffness locally, while potentially reducing residual stress and improving thermal behavior during fabrication. By leveraging the synergy between TO and stress field driven lattice infill, the design space expands to enable co-optimization of external shape, internal material distribution, and cellular architecture. Such a holistic approach results in components that are not only lighter and structurally efficient, but also inherently AM print-ready, requiring fewer supports and less post-processing without compromising mechanical performance, consistent with similar findings reported in [33] which were validated through both finite element simulations and experimental testing. This makes the proposed strategy particularly suitable for load-bearing aerospace applications, where weight reduction, structural integrity, and manufacturing practicality must be achieved simultaneously. Ultimately, this study underscores the need to balance automated computational optimization with practical manufacturing constraints, showing that coupling overhang-constrained topology optimization with self-supporting lattice infill can deliver lightweight, high-performance, and production-ready designs.

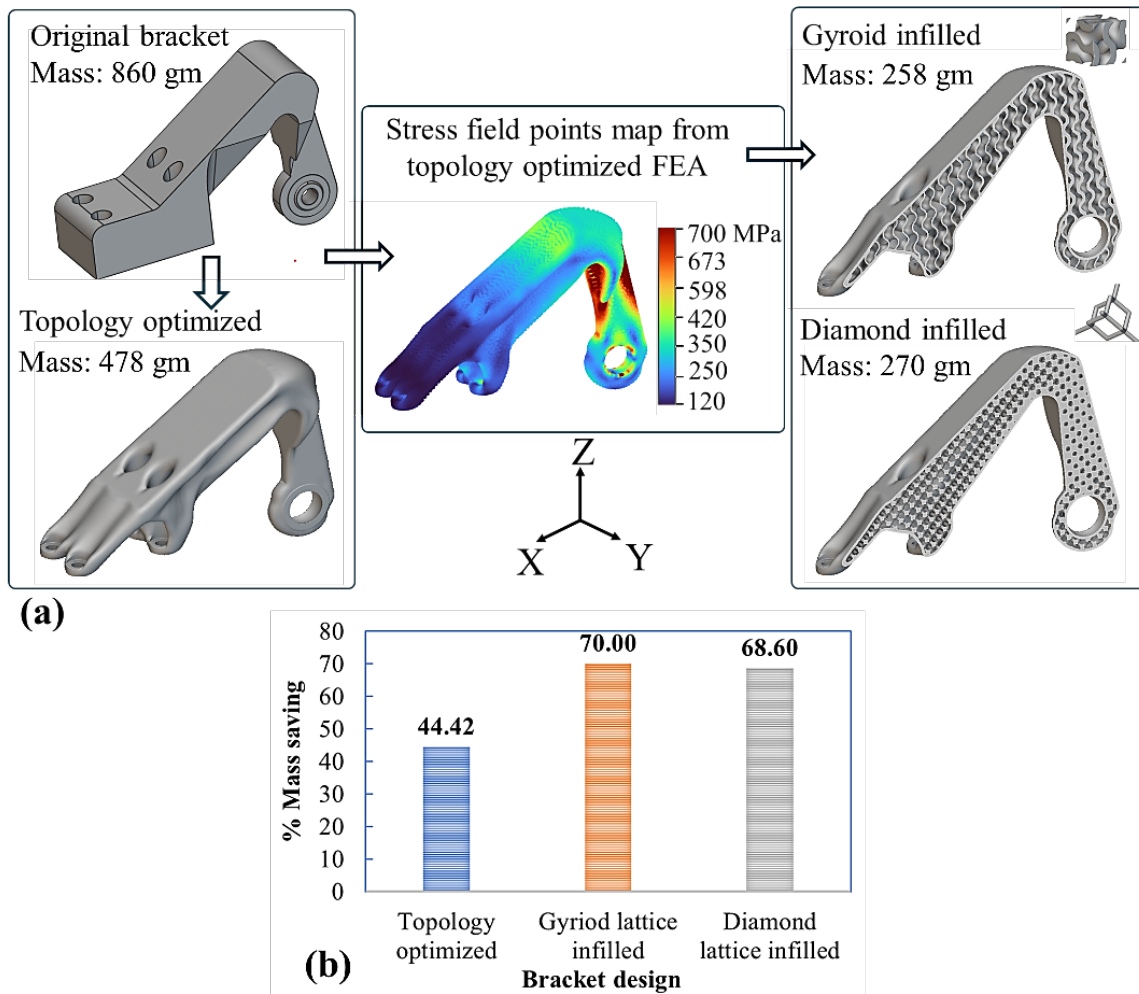


Fig. 3. (a) Design evolution of the bracket through a hybrid lattice design framework. The original bracket (860 gm) undergoes topology optimization, reducing its mass to 478 gm. The TO-derived geometry FEA stress is then used to guide field-driven lattice infilling, further reducing the mass to 258 gm for gyroid and 270 gm for diamond base lattice infilling, (b) Percentage mass saving compared to original bracket.

3.2 Performance evaluation

The FEA results in Fig. 4 highlight how the different design strategies influence both stiffness (deflection) and strength (von Mises stress). Fig. 4a shows that the maximum deflection remains within a narrow band for all configurations, indicating that the lightweighting strategies did not severely compromise global stiffness. The basic bracket exhibits a peak deflection of 2.20 mm, while the topology optimized bracket shows the highest deflection at 2.30 mm, reflecting the expected stiffness penalty associated with aggressive material removal and a more slender load path. In contrast, the gyroid lattice infilled design achieves the lowest deflection (2.19 mm), and the diamond lattice infilled design remains essentially at the baseline level (2.20 mm). These trends are also evident in the deflection contour plots in Fig. 5, which compare the deformation distribution for (a) the original solid bracket, (b) the TO bracket, (c) the gyroid lattice infilled bracket, and (d) the diamond lattice infilled bracket under the applied load case. This suggests that the lattice infill, when guided by the TO-derived field, can recover (or slightly improve) stiffness by stabilizing the load-carrying regions and improving internal support, even while maintaining substantial mass reduction.

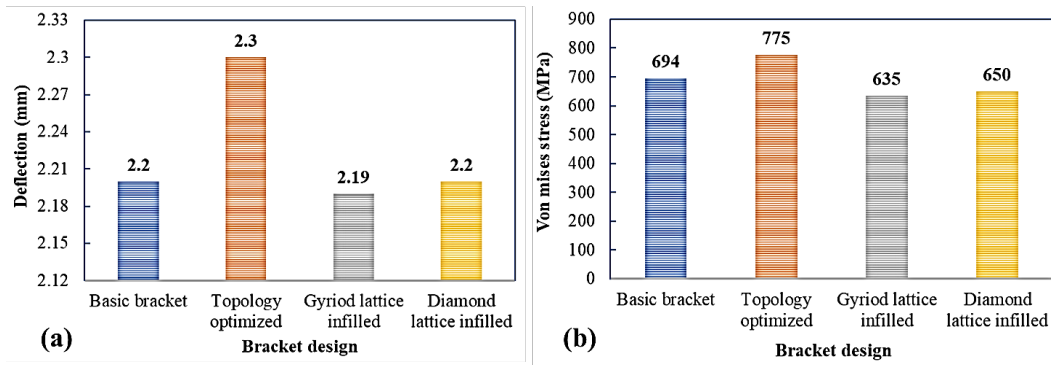


Fig. 4. Finite element comparison of structural response across bracket configurations. Charts show (a) peak von Mises stress and (b) peak deflection for the basic bracket, topology-optimized design, gyroid lattice infilled, and diamond lattice infilled.

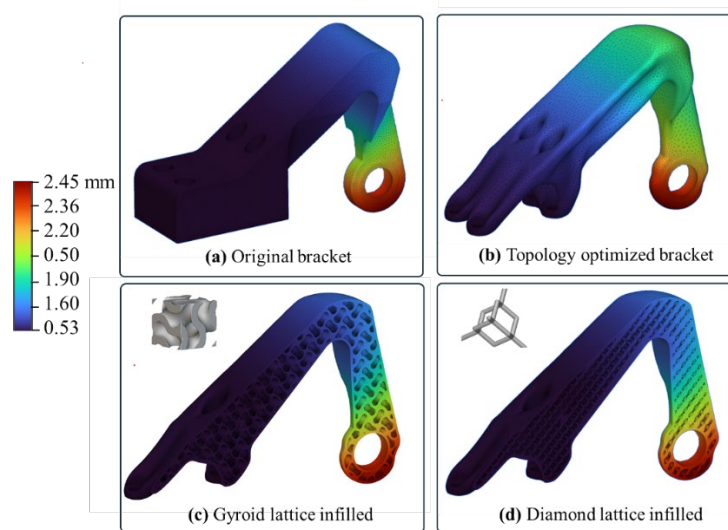


Fig. 5. Deflection contour plots for the bearing bracket under the applied load case, comparing (a) original solid bracket, (b) Topology-optimized bracket, (c) Gyroid lattice-infilled bracket, and (d) Diamond lattice-infilled bracket.

In addition, a more distinct contrast is evident in Fig. 4b for maximum von Mises stress, demonstrating how the different geometries redistribute loads and influence stress localization in the principal load paths. The TO only bracket exhibits the highest peak von Mises stress (775 MPa) primarily because the optimization targeted compliance minimization rather than stress reduction; consequently, material removal concentrates load transfer into slender load paths and introduces abrupt geometric transitions near constrained and loaded regions, which amplifies local stress concentrations despite maintaining acceptable global stiffness. The basic bracket shows a lower peak stress (694 MPa), benefiting from its more conservative, solid material distribution. Notably, both lattice infilled designs reduce peak stress relative to the basic and TO brackets: the gyroid lattice produces the lowest maximum stress (635 MPa), followed closely by the diamond lattice (650 MPa). This reduction indicates that the lattice architectures, tailored within the TO driven design space, promote more distributed load transfer and mitigate stress hotspots, particularly for the gyroid, where the continuous surface-based topology provides smoother stress flow compared to discrete strut junctions, consistent with the finding in [34]. This tendency is further visually supported in Fig. 6, which presents a comparative von Mises stress contour assessment for all bracket designs, including both isometric and cross-sectional views for lattice infilled designs, enabling direct evaluation of stress distribution and hotspot locations across the different configurations. Inclusive, these results demonstrate a favorable trade-off: TO alone achieves weight reduction but at the cost of higher stress and deflection, whereas lattice infill not only delivers larger weight savings but also reduces peak stress and maintains stiffness comparable to the baseline. Importantly, all designs remain below a

1000 MPa yield threshold, with implied safety margins of approximately 1.29 (TO) to 1.57 (gyroid), supporting the feasibility of the optimized, print-ready concepts for load-bearing applications where mass efficiency is critical.

Taken together, the comparative results show that mass reduction and mechanical response do not improve in the same way for all strategies. The TO only design achieves a clear reduction in weight, but this comes with the highest peak stress and largest deflection indicating that compliance driven TO solution can concentrate load into slender paths and amplify local stress levels. When lattice architectures are introduced within the TO derived design space, the outcome becomes more balanced: both lattice designs deliver substantially greater weight savings while lowering peak stress and keeping deflection essentially at the baseline level, a similar observation is presented in [35]. In other words, lattice infill acts not only as a lightweighting mechanism but also as a structural regularizer providing internal support that promotes smoother load transfer and reduces stress peaks most notably for the gyroid configuration, which exhibits the lowest peak stress among the studied designs [36]. However, these conclusions should be interpreted critically: peak stress metrics from linear static FEA do not capture potential fatigue performance, local buckling of thin features, node/strut stress amplification, or manufacturing induced defects, all of which can govern lattice based components in practice. Moreover, the apparent benefit of each lattice type is parameter dependent (cell size and thickness bounds), meaning the reported performance is specific to the selected feasible ranges that met the design constraints. In conclusion, the study supports the view that TO defines the global structural concept, but field guided lattice tailoring is required to achieve print-ready, high efficiency designs, provided that follow on validation (fatigue, manufacturability, and test correlation) is performed before aerospace deployment.

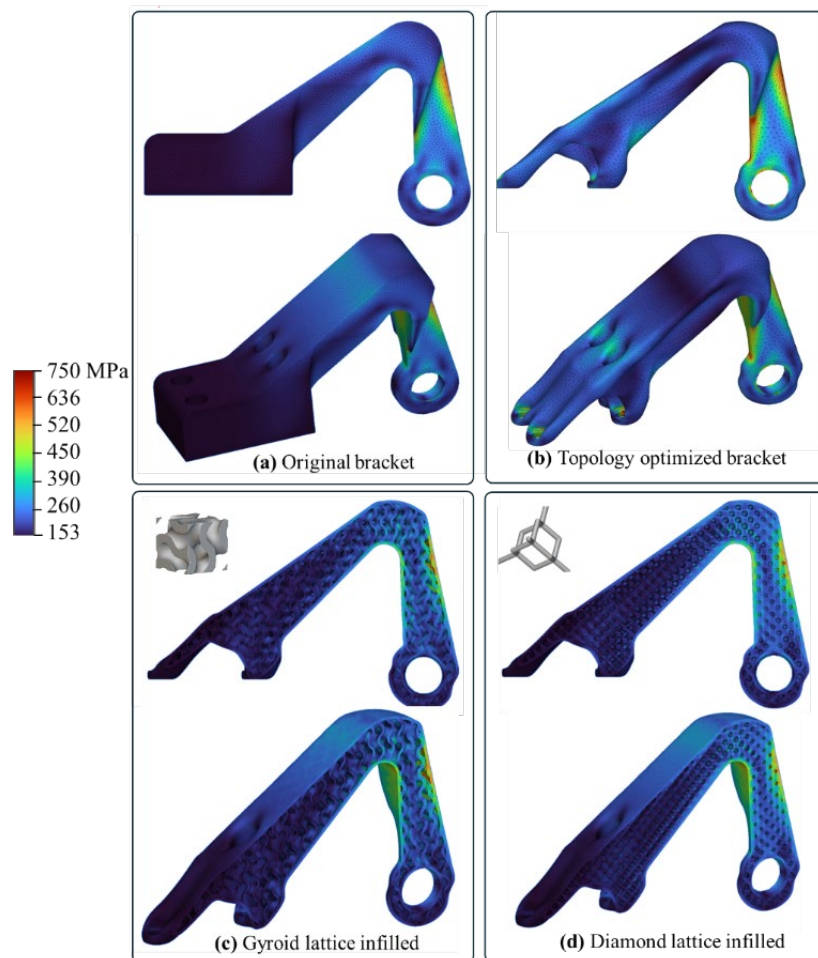


Fig. 6. Comparison of von Mises stress distributions obtained from FEA for all bracket configurations. For each design, front and isometric views are presented: (a) Original, (b) Topology-optimized, (c) Gyroid lattice infilled, and (d) Diamond lattice infilled.

4 Conclusion

This study demonstrates the importance of combining topology optimization with novel field guided lattice infill to achieve lightweight, AM ready bracket designs for aerospace applications. Relative to the baseline bracket, TO reduced mass by 44.42%, while the lattice infilled designs achieved substantially larger savings of 70% (gyroid) and 68.6% (diamond), showing that micro-architectural tailoring can extend lightweighting beyond TO alone. Importantly, the mechanical response remained well controlled: TO alone produced the highest peak stress (775 MPa) and deflection (2.30 mm), whereas the gyroid and diamond lattice designs reduced peak stress to 635-650 MPa while maintaining deflection near the baseline (2.19-2.20 mm). These results indicate that compliance driven TO improves material efficiency but does not necessarily minimize stress peaks, and that lattice infill can mitigate stress hotspots while preserving global stiffness. Crucially, this was enabled by an automated, nTop-driven workflow in which the TO-derived stress field is mapped directly to spatially varying lattice parameters, allowing rapid, repeatable lattice tailoring without manual trial-and-error. Manufacturability was explicitly addressed through an overhang constraint during TO to reduce required supports, and through the use of self-supporting lattice architectures, yielding geometries that are more directly compatible with metal additive manufacturing and reduced post-processing effort. To conclude, the proposed workflow provides a scalable route to co-optimize external topology and internal cellular architecture for mass-critical structures. While the conclusions are based on linear static FEA, the results motivate follow on validation under fatigue, damage tolerance, and manufacturing variability to confirm in service performance. Nonetheless, the demonstrated weight reductions with maintained stiffness and reduced peak stress show that integrating TO with lattice infill is a promising, practical strategy for next generation lightweight aerospace components.

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