



A New Lightweight Design Methodology to Produce Fail-safe Additively Manufactured Parts in Industry: A Case Study of a Motorcycle Brake Lever

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Abstract. The durability of additive manufacturing (AM) parts has been a major issue with the prospect of being produced in a highly demanding and competitive industry over the last twenty years. Materials of AM are also a very crucial aspect for enabling complex designs, reducing waste, and enhancing production efficiency. One of the most advanced methods of improving the durability of products and minimizing mass is the use of lattice structures, as a new approach among generative design alternatives and topology optimization. On the other hand, fail-safe structures require particularities in their durability to remain functional under normal or instantaneously loading conditions. Under such conditions and restrictions, it would be expected that, through AM technology, the manufacturability and customizability of such products would be more feasible than expected. However, fail-safe parts remain unexplored scientifically in the field of AM, despite the prospects of numerous applications they could have in industry. The current study is concerned with the control of durability in specific internal areas of extrusion-based AM parts using the concept of design intent, with the prospect of becoming fail-safe products, without distorting the original external form of the products. A new, four-step methodology is proposed based on the use of the meaning of design intent and the insertion of parameterized lattice structures in specific calculated areas of the inner structure of the part, consequently affecting the behavior of the product during its failure. Comparison with traditional methodologies reveals the advantages of the proposed methodology, which can also be applied to other sectors of industry, enabling more products to acquire the status of being fail-safe.

Keywords: lattice structure, fail-safe, additive manufacturing, design intent

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1 INTRODUCTION

Additive Manufacturing technology is transforming how industrial products are made, designed, worked, and repaired, as important derivatives of the fourth industrial revolution. The emergence of AM technology in mass production was inevitable due to its competitive and unique features that were directly related to the reduction of production cost, such as the low energy consumption, the

minimized material waste, and the elimination of special tools during the production process [3]. In contrast, low durability remains one of the greatest barriers, among other factors, to AM technology's widespread adoption and acceptance in industry [6]. Although additive manufacturing technology exhibits relatively low mechanical strength and durability, it remains at the cutting edge of technological advancement due to its exceptional design customizability and the ability to produce items on demand without the need for specialized tooling, thereby offering groundbreaking performance and unmatched design flexibility. The mechanical properties of these materials are highly dependent on the deployment of the internal geometry during the building process, which also affects the cost and the quality of the produced parts [2].

In all approaches, the weight and durability of the parts proved to be the main factor of production cost, and many studies have been conducted for the reduction of the materials' weight using numerous methodologies and techniques due to the cost reduction potential of extrusion-based AM parts in the field of structural optimization of parts focusing on lightweight and robust designs. One of the most advanced methods of improving the durability of products and minimizing mass is the use of lattice structures, as a new approach among generative design alternatives and topology optimization [8],[13]. These structures have the advantage of reducing the weight of the original part and simultaneously maintaining their strength [11]. Among all these methods, latticing has become a key factor in reducing the weight of produced parts, and numerous software associated with AM machines have incorporated this approach to managing product durability and build time. Primary building parameters such as infill pattern, infill density, and secondary parameters such as layer thickness and building orientation, among others, are also used by AM software to control the building process with the prospect of optimizing time, cost, and durability of additively manufactured parts [6]. The building features of the produced components are defined by specially designed software, coding the manufacturing process of the AM machines [13], and a widely used building feature that forms the interior part of the produced object is the lattice structure. More specifically, a lattice is a cellular material characterized by the repetition of a specific unit cell form on a design pattern [9], which can be controlled by numerous building parameters, such as infill density and infill pattern [6]. The significant advantages of the lattice structures include the high strength-to-weight ratio, the notable absorption of energy of the manufactured lattice parts and the minimization of material requirements [7]. With the use of lattice structures, the produced part's weight is reduced, and its durability and building time are controlled by AM software tools [6]. The lattice structures are mainly characterized by complex geometries, which provoke manufacturing limitations that can be overcome by AM technologies, which, in general, provide the ability to produce parts that are impossible to build by traditional manufacturing processes [3]. Nevertheless, building lattices has numerous restrictions due to the software of AM machines. Existing AM software does not provide the capability of applying a variety of distinct values of infill pattern parameters to different areas of the inner surface or applying different shell thickness to inner and outer surfaces of the parts, which leads to losing control over their strength, their resistance and stiffness, and thus, no control of the production cost or the ability to construct fail-safe products [3],[9].

Fail-safe structures require particularities in their durability to remain functional under normal or instantaneously loading conditions. Under such conditions and restrictions, it would be expected that, through AM technology, the manufacturability and customizability of such products would be more feasible than expected. However, fail-safe parts remain unexplored scientifically in the field of AM, despite the prospects of numerous applications they could have in industry [8],[4].

The limitations of AM software are a key reason that AM technology is not capable of producing fail-safe objects automatically, and are predominantly manufactured, often without recognizing that AM customization could endow them with distinctive properties. Fail-safe is a design principle, according to which the product should include advanced features providing safety that can be applied to various engineering structures, ensuring the protection of the structure to a decent level, when it is being damaged [7] [10]. In this paper, a new lightweight methodology is therefore described, based on the insertion of multi-Lattice structures in an AM product, using topology optimization tool and the meaning of design intent to define the areas and the parameters of the geometry needed to make a product fail-safe, replacing regions of the structure with bodies which are then converted

into parameterized lattices. The developed methodology has been applied to a motorcycle brake lever and compared with traditional methodologies such as generative design and topology optimization. CAE simulation and parametric CAD systems were used to identify and customize the internal geometry of the part with the principle to become a fail-safe product with what this entails to produce similar products in industry.

2 DESCRIPTION OF THE PROPOSED METHODOLOGY (4-STAGES)

The proposed methodology is described in four main stages as followed, parametric modelling, mechanical analysis for body areas selection, lattice insertion and lattice optimization with the prospect to transform a product into a fail-safe, considering its function and performance, which is to remain active in use even after its failure, giving the ability to the system, to reuse the product and continue its operation, Figure 1.

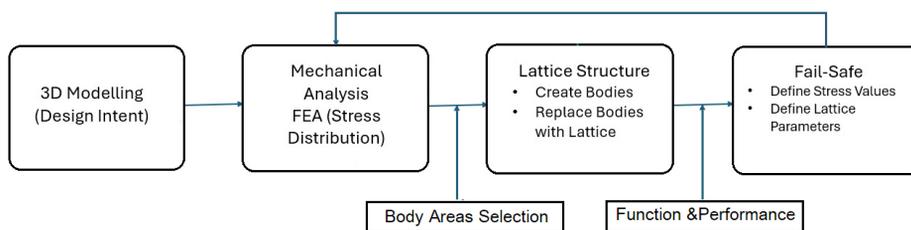


Figure 1: Four-Step methodology, transform a simple part into a fail-safe product.

The design process begins with the definition of all geometric parameters and constraints that characterize the product. These inputs are incorporated based on the principle of design intent using a parametric CAD system, such as Creo Parametric (PTC), which facilitates the creation of fully associative and easily modifiable geometries. It's also important to include all the right parameters for the structural analysis so that the model is ready to be tested in the simulation. Once the parametric CAD model is complete, a static structural analysis is carried out using the Creo Simulate module, which is based on the finite element method (FEM).

The second stage plays a key role in identifying critical regions based on stress distribution. Simulation results highlight both high-stress concentration zones that are potential sites for fatigue failure such as low-stress areas that contribute minimally to the part's structural integrity. It's important to recognize that stress patterns vary depending on the geometry and loading conditions of each specific design. Understanding these patterns provides valuable guidance, low-stress regions may be targeted for material reduction or topological optimization, while high-stress areas indicate where design reinforcement may be needed to improve durability and performance.

Before advancing to the third stage of the methodology, we must clearly define the most structurally significant regions. This is based not only on the static analysis results but also on the intended failure behavior of the part, especially given our goal of reducing overall mass.

Our approach is to remove the largest amount of material from regions with low stress distribution and a smaller amount from areas experiencing higher stress. This strategy is designed to allow the part to fail in a controlled and predictable way when subjected to a specific load. The modified regions are then replaced with lattice structures, whose strength can be adjusted by changing their shape and size.

Using a CAD system, we redesign the internal structure of the part, a process that can be time consuming and often require advanced modeling skills. To simplify and accelerate this step, we introduce basic solid shapes, referred to as "bodies," which offer two key advantages. First, they are

easy to create and position within the desired regions of the part. Second, they can be quickly replaced with parameterized lattice structures. To ensure the product behaves in a fail-safe manner (failing in a controlled and non-hazardous way) we must optimize the inserted lattices. This involves adjusting their defining parameters to achieve the desired mechanical response. For this reason, we perform another finite element analysis (FEA) to validate the design.

The simulation results confirm the fail-safe behavior of the modified geometry. Thanks to additive manufacturing (AM) technology, producing this customized structure presents no fabrication challenges.

3 IMPLEMENTATION OF THE METHODOLOGY: CASE STUDY OF A MOTORCYCLE BRAKE LEVER.

More specifically, using the Creo Parametric CAD system, a parameterized motorcycle brake lever was designed using the meaning of design intent to insert all the design information needed to accomplish the desired geometry, Figure 2. Using Finite Element Analysis, stress distribution under an impact was evaluated, simulating the fall of the motorcycle while riding, applying an average force of 1500 N at the ball structure of the handle lever [1],[12]. Lattice creations were then inserted using specific CAD entities called "bodies" in three different areas of the structure, to reduce total mass of the part at the areas where stress concentration was located and to control the damage status of the remaining part near the falling areas. Using an optimization study through an FEA system, we succeeded in finding the optimum values of design parameters that defined each lattice structure of the part to control the durability of the brake lever and to make it a fail-safe product. In this case, we selected the thickness of each lattice as the primary and most effective parameter for the strength and mass of the part.

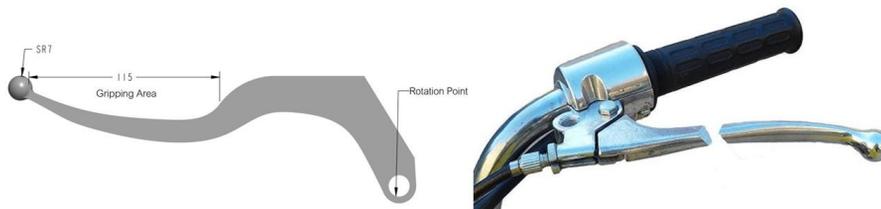


Figure 2: Motorcycle handle lever main geometry and failure after impact.

Material selection of the motorcycle brake lever

The product we are testing is a motorcycle brake lever, which allows riders to stop or slow down while they are riding a motorbike. They are usually made of low-cost aluminum-silicon (Al-Si) alloy material, which finds a great number of applications in aerospace, automotive, and similar sectors in industry, due to a good combination of mechanical properties, such as low weight, high heat conductivity, and excellent corrosion resistance. The most common aluminum alloy used in automotive is Al-12Si, which has similar mechanical properties to AlSi10Mg that is used in AM technology. Furthermore, Al-Si alloy with magnesium enables Mg₂Si precipitation to increase the strength of the material without affecting the other mechanical properties [5]. AlSi10Mg contains 0.45 to 0.6 wt.% Mg, and it is easy to process by laser applications having a small solidification range, compared to high durability aluminum alloys [1],[8]. We therefore chose to conduct our measurements with AlSi10Mg since it's compatible with AM technology materials and has similar mechanical properties to Al-12Si, which is commonly used in industry, Figure 2, Table 1.

Stress distribution using FEA

Using Creo Parametric CAD system and the meaning of design intent a parametric geometry of a common motorcycle lever was developed. The end of the brake lever has a spherical geometry with

a diameter of 14mm, and the gripping area has a maximum width of 115mm, [1],[12]. The material used was AlSi10Mg with the properties shown in Figure 3 and Table 1. The material was modelled as elastoplastic, taking the average values of the stress-strain curves of Figure 3. The applied force was 1500 N and the right side of the level was fixed (zero degrees of freedom). The FEA analysis using Creo Simulate reveals that there are three distinct areas as shown in Figure 4.

The Tensile force was applied on the surface of the spheroidal geometry as would happen if the motorcycle fell. The total mass of the part was calculated to be 91,45gr. The results show high stress concentration in Areas A & B and low stress concentration in Area C. The stress concentration in all areas didn't exceed the UTS (391MPa) of the material but exceeded the yield stress (270MPa) of AlSi10Mg material close to area A, meaning that a plastic deformation occurs, table 2.

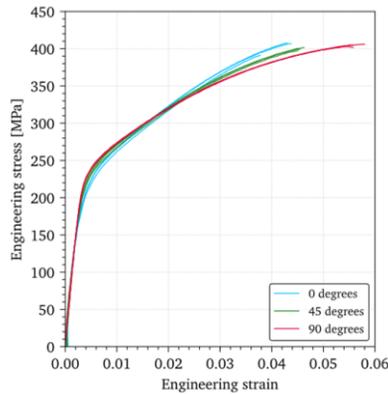


Figure 3: Engineering stress-strain curves up to failure of the AlSi10Mg at 0,45, 90 degrees with respect to the printing direction [4].

Material	Young's Modulus (E)	Density (p)	Yield Strength (YS)	Ultimate Strength (UTS)
Al-12Si	75GPa	2.65g/cm ³	267+/- 10MPa	369+/- 15MPa
AlSi10Mg	68GPa	2.68g/cm ³	270+/- 10MPa	391+/- 15MPa

Table 1: Mechanical properties of Al-12Si and AlSi10Mg.

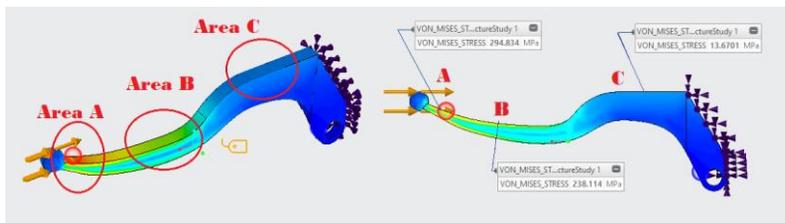


Figure 4: Stress distribution at three distinct areas, A, B and C.

Area	A	B	C
Maximum stress	294.8MPa	238.1MPa	13,6MPa

Table 2: Maximum stress in areas A, B, and C.

Bodies and Lattice insertion

Using the Creo Parametric CAD system, three different body structures in areas A, B, and C were inserted in Figure 5. These bodies were then replaced with lattice structures to reduce the total mass of the overall product, using a minimum square lattice wall thickness of 0.4mm to respect AM constructive limitations when using metal materials, and with the greatest reduction in mass occurring in area C, considering the stress distribution that was found in the previous section, Figure 4.

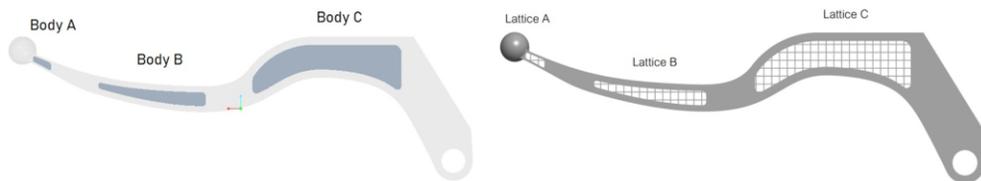


Figure 5: Replacement of bodies with lattices.

Optimized lattice structures to incorporate Fail-Safe principles

Fail-safe design principles ensure product safety by incorporating features that maintain functionality and prevent hazards even during failures. In the scenario we are studying, the product needs to fail(brake) in region A, under an impact of 1500N of force during a motorcycle's fall, thereby preventing the transfer of force to the rest of the motorcycle and avoiding further damage. Simultaneously, we need to maintain functionality of the brake handle, and for that reason, region B should exhibit minimal plastic deformation, ensuring that the brake handle remains operational for use after a fall. More specifically, to accurately determine the values of developing stress during the analysis, we need to specify variables and conditions under which the data is collected and analyzed, ensuring that the results are both reliable and valid. For that reason, we inserted two reference points attached at the surface of the brake lever where areas A and B are located. These points were used to measure the average stress levels at areas A and B, where the lattices are located, and were also used for the optimization study that followed. The goal was to minimize the mass and keep the maximum stress concentration on area A, close to the tensile strength of the material, and on area B, close to the yield strength, to ensure that when the product fails, it will remain functional. This means that the product can be characterized as fail-safe while, at the same time, we reduce the minimum possible weight. The main parameters for the optimization study of the two lattices (A&B) were the values of the lattice thickness, since it is directly related to the mass of the product, but it can also significantly affect its strength. The optimized geometry is shown in Figure 6.

4 REDUCTION TECHNIQUES IN ADDITIVE MANUFACTURING VS. SUGGESTED METHODOLOGY

The research on lightweight mechanically robust components in AM has led to the convergence of advanced design methodologies and processes. Central to this evolution is the use of CAD and CAE systems, which enable the development of geometrically complex structures informed by performance-driven simulations.

New additive manufacturing (AM) processes increasingly use topology optimization and generative design. These techniques use algorithms to explore many design options and find shapes that use less material while still performing well. Unlike traditional design methods, they rely on computational intelligence to create structures that are both efficient and effective [13]. At the same time, internal structures like lattices and graded infill patterns are being used to reduce weight even more. These designs are created with specialized AM software and are optimized to handle mechanical loads with minimal material. Their development is guided by simulations that consider stress, heat behavior, and manufacturing limitations [8].

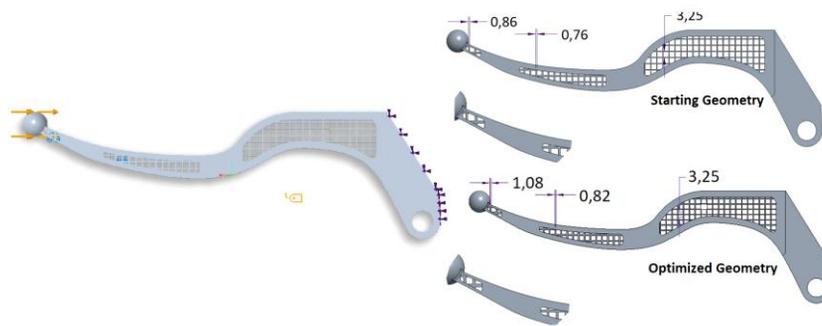


Figure 6: Optimized lattice to integrate fail-safe principles.

Nevertheless, although these techniques significantly reduce the overall mass of a component, they are unable to preserve the original geometry of the product. As a result, the outcome often constitutes an entirely new design. Furthermore, the mass optimization process does not allow the designer to intervene in specific regions of the part to locally control material distribution and, consequently, the mechanical behavior. This limitation restricts the ability to engineer the structure for fail-safe performance. In contrast, the use of internal lattice structures, typically generated by software integrated with AM systems, can minimize mass while maintaining the external geometry of the original design, since the lattice is embedded internally. However, these tools generally lack the capability to define localized lattice configurations in targeted areas. The proposed methodology presented in this study addresses the limitations of the approaches. It enables mass reduction, preserves the original geometry, and allows for localized control of structural strength, as demonstrated in the following analyses.

The four-step method proposed in the preceding sections of our study not only reduces the mass required for product manufacturing, yielding significant industrial benefits, but also imparts fail-safe properties to the products. This necessitates an evaluation of our method against two of the most prevalent and robust mass reduction techniques in additive manufacturing technology, such as the insertion of internal lattice structures throughout the solid mass through software that accompanies AM machines and the application of topological optimization via generative design methodology, both of which represent innovative advancements in the field of mass reduction in AM technology.

To this end, elastoplastic analyses were conducted for each method using the same brake lever for the same mass, 67,10gr under the same value of Force 1500N and the same material, AISi10Mg. The results of the analysis are shown in Figure 7.

From the analysis presented in the previous sections of our study, Table 2, it is evident that for the brake lever without internal lattices, the stress developed at points A and B is either below or close to the yield strength value and significantly below the ultimate tensile strength (UTS) value. This indicates that the lever will neither fail nor undergo significant plastic deformation, thereby transferring the force to the motorcycle's handlebars and potentially causing damage, an undesirable outcome we aim to prevent.

Our conducted analysis reveals that when specific lattices are inserted at selected areas according to the proposed Four-Step methodology, the scenario suggests failure near point A, as it exceeds the ultimate tensile strength, and minimal deformation near point B. This allows the brake lever to remain functional even after the motorcycle's fall, making the product fail-safe with full control over strength distribution. This is achieved by controlling the parameters and areas where the lattices are inserted, guided by design intent. Using the second methodology, which involves lattice insertion throughout the entire structure of the product, there is no ability to target specific areas due to the limited capabilities of the additive manufacturing machine software. Based on the stress values at points A and B from the conducted analysis, the brake lever would undergo plastic deformation in all areas, making it non-functional after a fall.

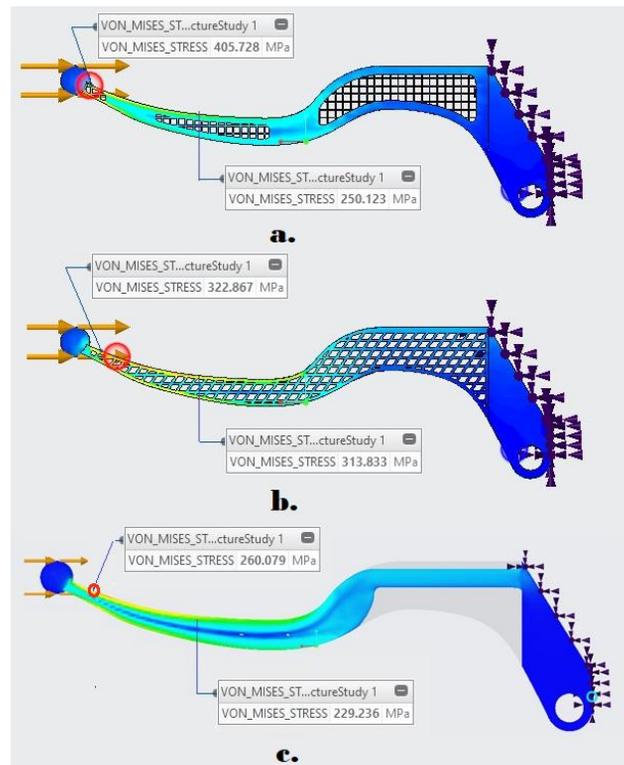


Figure 7: a. Four-Step methodology, b. Lattice insertion methodology, c. Generative Design methodology.

According to the third methodology, which minimizes mass using generative design algorithms, the stress distribution shows that the stress value remains in all areas below yield strength and UTS, which indicates almost the same mechanical behavior as the brake lever with no lattice at all, table. 3. The produced geometry using generative design also deforms the product, and the aesthetic result is different than the expected one, and the control of stress distribution in specific areas to become a fail-safe product is impossible.

<i>Areas</i>	<i>A</i>	<i>B</i>
Four-Step Methodology	405.7MPa	250.1MPa
Lattice Insertion Methodology	322.9MPa	313.8MPa
Generative Design Methodology	260.1MPa	229.2MPa

Table 3: Maximum stress at areas A and B for each methodology.

5 CONCLUSIONS

This study introduces an innovative lightweight design methodology for producing fail-safe additively manufactured parts, exemplified by a motorcycle brake lever. By employing multi-lattice structures and optimizing mechanical parameters through finite element analysis and the meaning of design intent, the methodology significantly enhances structural integrity and reduces mass. Simultaneously, additive manufacturing products are endowed with the distinctive capability of becoming fail-safe. This approach demonstrates substantial potential for advancing mechanical engineering applications, particularly in sectors requiring high performance, reliability, and safety, such as aerospace and automotive industries, and unveiling new possibilities in the application of additive manufacturing technology in industry.

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