Title:
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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Introduction:
Additive Manufacturing technology is transforming how industrial products are made, designed, used, and repaired, as an important derivative 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 low energy consumption, minimized material waste, and the elimination of special tools during the production process [3]. 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]. One of the most advanced methods of improving the durability of products and minimizing the mass is the use of lattice structures, which have the advantage of reducing the weight of the original part and simultaneously maintaining structural integrity [6]. More specifically, a lattice is a cellular material characterized by the repetition of a specific unit cell form on a design pattern, being able to be controlled by numerous building parameters, such as infill density and infill pattern, among others, defined through specialized software [5]. 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. Unfortunately, the limited capabilities of software that accompanies AM machines along with the layer upon layer material deposition method in combination with the geometric complexity of many parts, makes the overall process difficult to construct a wide range of industrial parts in many fields, like aerospace, biomedical plants, even fail-safe products, etc. [3]. Fail-safe structures require particularities in their durability to remain functional, under normal or instantaneously loading conditions [7]. 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. 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. CAE simulation and parametric CAD systems were used to

identify and customize the internal geometry of the part with the principle of being a fail-safe product, considering what this entails to produce similar products in the industry.

Description and implementation of the proposed method:
The proposed methodology is described in four main stages as followed, parametric modelling, mechanical analysis, lattice insertion and finally lattice optimization with the prospect to transform a motorcycle brake lever into a fail-safe product, considering its function and performance, which is to remain active in use even after its failure giving the ability to the motorcycle rider to reuse the product and continue his journey, fig.1. More specifically, using a 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, fig.2. Using Finite Element Analysis, stress distribution under an impact was evaluated. The impact refers to the fall of the motorcycle during riding and was simulated by an average force of 1500 Nt at the ball structure of the handle lever [1]. Lattice structures were inserted using specific CAD tools (bodies) in three different areas of the structure, to reduce the 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, the optimum values of each lattice structure were found with the principle of becoming fail-safe.

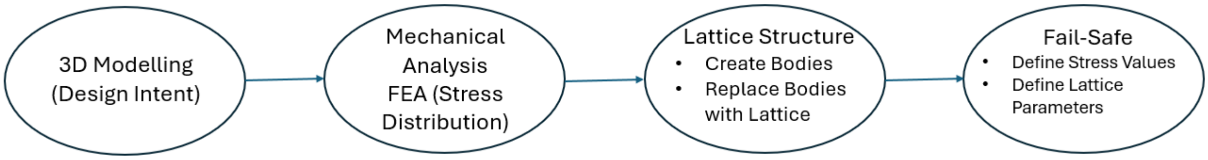

Fig. 1: A four-step methodology, transform a simple part to fail-safe.

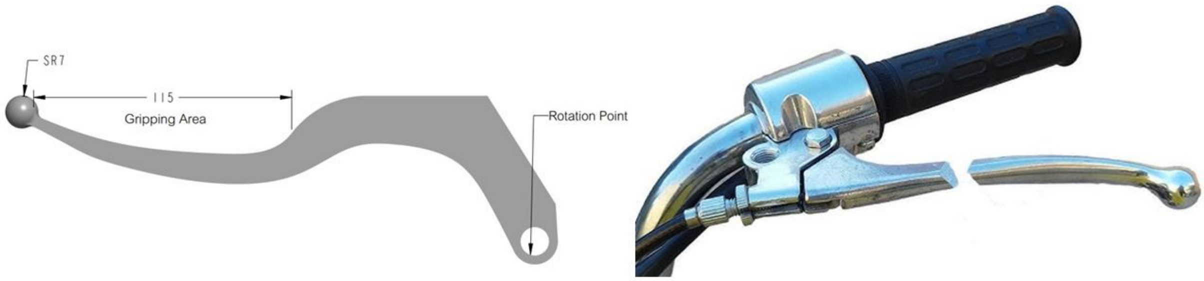

Fig. 2: Motorcycle handle lever main geometry and failure after impact.

Material selection of the motorcycle brake lever:

The product tested is a motorcycle brake lever, which allows riders to stop or slow down while they are riding a motorcycle. 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, which 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. 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]. The analyses were, therefore, conducted using the AlSi10Mg material due to its compatibility to AM technology and having similar mechanical properties with Al-12Si, fig. 3, Table 1.

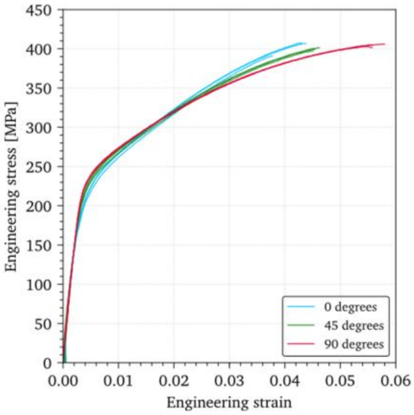

Fig. 3: Engineering stress-strain curves up to failure of the AlSi10Mg at 0,45, 90 degrees concerning the printing direction [4].

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

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

Stress distribution using FEA**:**

Using the 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. The material used was AlSi10Mg with the properties shown in Table 1. The applied force was 1500 N · t, and the right side of the lever was fixed (zero degrees of freedom). The FEA analysis using Creo Simulate reveals that there are three distinct areas, as shown in Fig. 4. In area A, there is a high stress concentration with the stress exceeding the yield strength of the material. Area B has a lower stress concentration, whereas area C has very low stress [1].

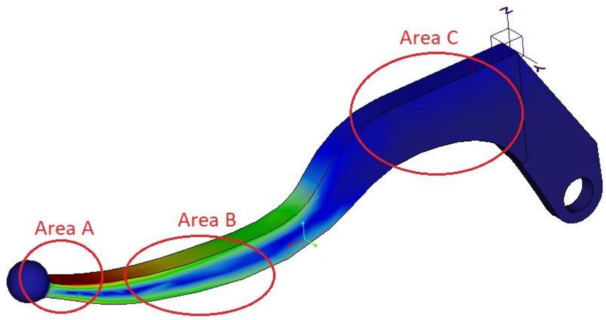

Fig. 4: Stress distribution at three distinct areas, A, B and C.

Bodies and Lattice insertion:

Using Creo parametric Cad system, three different bodies structures at the areas A, B and C were inserted, fig. 5. These bodies were then replaced with lattice structures to reduce the total mass of the overall product, with minimum square lattice wall thicken at 0.4mm to respect AM constructive limitations using metal materials and with the greatest reduction in mass occurring in the area c.

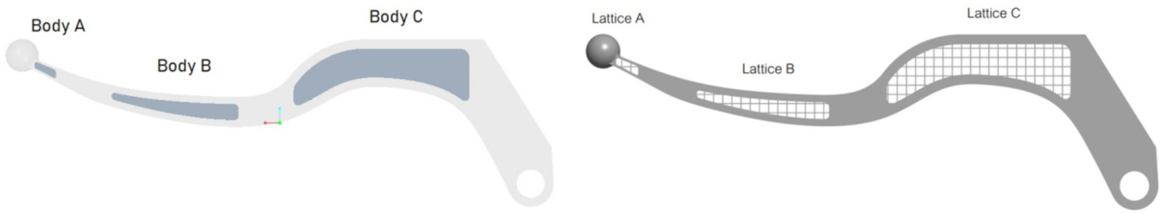

Fig. 5: Replacement of bodies with lattices.

Optimized lattice to become a fail-safe product:

Following, multiple reference points attached to the surface of the brake lever were inserted. These points were used to measure the average stress levels at specific areas of the lattice structures A and B 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. That means that the product can be characterized as fail-safe while at the same time reducing the minimum possible weight. The main parameters for the optimization study of the two lattices (A&B), was the value of the lattice thickness, since it is directly related to the mass of the product, but it also significantly affects its strength. The optimized geometry is shown in fig. 6.

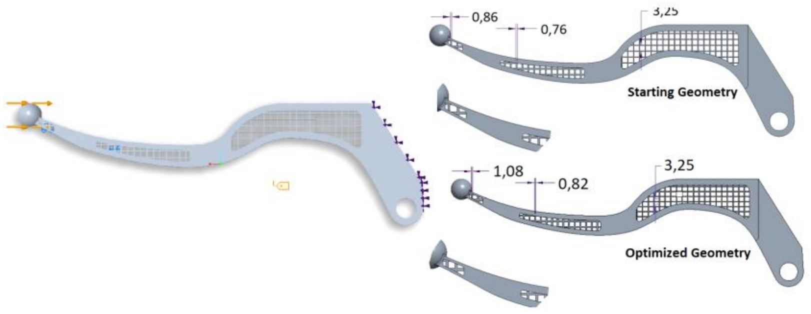

Fig. 6: Optimized lattice to become a fail-safe product.

Evaluation of the suggested method with existing reduction methods in additive manufacturing:
The four-step approach outlined in the previous sections of our research not only decreases the mass required for product manufacturing, resulting in substantial industrial advantages, but also enhances the fail-safe characteristics of the products. This necessitates a comparison of our method with two of the most widely used and effective mass reduction techniques in additive manufacturing technology: the integration of internal lattice structures using software that accompanies AM machines, and the application of topological optimization, fig. *7*

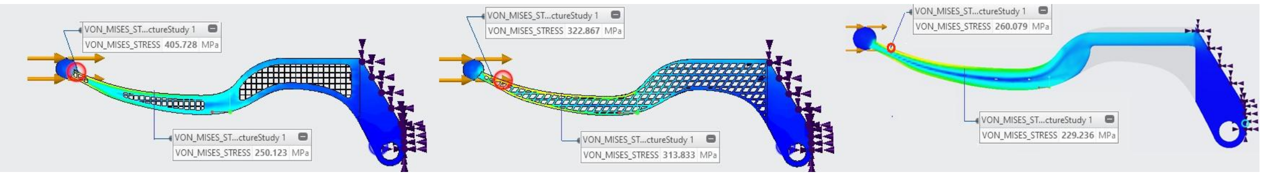

Fig. 7: 4 step method, Insertion of lattice method, Topology optimization, stress distribution.

The analyses in all three cases demonstrated that only the proposed method achieves the desired operational scenario of the object, with failure occurring at position A and minimal plastic deformation at position B.

Conclusions:

This study introduces an innovative lightweight design methodology for fail-safe additively manufactured parts, exemplified by a motorcycle brake lever. By employing multi-lattice structures and optimizing mechanical parameters through finite element analysis, the methodology significantly enhances structural integrity and reduces mass. This approach demonstrates substantial potential for advancing mechanical engineering applications, particularly in sectors requiring high performance and reliability, such as the aerospace and automotive industries.

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