DESIGN AND TOPOLOGY OPTIMIZATION FOR ADDITIVELY MANUFACTURED STRUCTURAL PARTS: A FORMULA STUDENT CASE STUDY

[1]H. Bikas, [1]J. Stavridis, [1,2]P. Stavropoulos and [1] G. Chryssolouris[**]

[1] Laboratory for Manufacturing Systems and Automation, Department of Mechanical Engineering and Aeronautics, University of Patras, Patras, 26500, Greece,
[2] Department of Aeronautical Studies, Hellenic Air Force Academy, Dekelia Air-Force Base, TGA 1010 Athens, Greece,
** Corresponding author. Tel.: +30 2610 997262; fax: +30 2610 997744. *E-mail address*: xrisol@lms.mech.upatras.gr

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ABSTRACT –
Formula Student is a worldwide project for engineering students to design, build and race a small single seater racing car. The teams have to cope with rules and restrictions which concern specifications of the car such frame, engine and safety. Motorsport sector demands lightweight vehicle concepts without sacrificing performance. In that direction, high stiffness-to-weight ratio must be accomplished to almost every component of the car. Consequently, the design for manufacturing is crucial to Formula Student teams. Additive Manufacturing (AM) is a technology that can effectively meet the requirements for reduced weight and high stiffness components, in contrast with convectional manufacturing processes such as milling or turning. In this work, the main guidelines for designing an Additively Manufactured part are presented and optimization techniques using ANSA and Tosca software tools are analyzed, in order to propose a redesign for a structural part of a Formula Student racecar based on AM. The AM process advantages and the flexibility offered in designing and manufacturing of complex components lead to a lighter structural part, achieving equivalent stiffness validated following extensive FEA analysis. Finally, this work tries to overcome implications of current CAD programs that are considered inadequate for designing for AM and explore the design freedoms of AM in order to get the most out of it.

1. INTRODUCTION

Formula Student is a worldwide competition where students design build and race their own open wheel race car (1). Each of the competitions is divided in static and dynamics events. Static events cover the sections of cost, presentation and design. During design event the teams present their engineering solutions justifying their choices. In presentation event the business plan for a potential investment of manufacturing the car is introduced. Finally the aim of cost event is to fully exploit the cost of materials, manufacturing processes and tooling that were used for the manufacturing of the car. Dynamic events (acceleration, skid pad, autocross, fuel economy and endurance) on the other hand, test the performance of the car and student drivers on-track (1). As a result the competitions dictate that success is highly depended on the balanced design and development decisions of all the aspects of the car.
In that direction one of the main decisions that concern the activities of a Formula Student team is the design and manufacturing of car’s structural components. These parts have to withstand great forces and moments providing adequate strength and stiffness under various types of loads. In addition to this, the particular components need to be lightweight in order to keep the total weight of the car as low as possible for performance reasons. Therefore is crucial for the Formula Student teams to efficiently combine creative thinking with the available manufacturing resources in order to achieve a satisfying stiffness-to-weight ratio.

As a result, design for manufacturing approach has to be taken into account by the team members, leading to decisions which will minimize manufacturing difficulties and associated costs (2).
Milling and casting are well-established processes (3) which depict usual manufacturing alternatives utilized for these applications. However, Additive Manufacturing (AM) has currently gained a lot of attention in industry and is one of the fastest growing and promising manufacturing technologies (4). The wide spread that AM has established so far, is due to the process flexibility in manufacturing complex geometries, questionable or even impossible to be manufactured using convectional processes. Consequently, benefits such as design freedom, customized components, reduced processing and assembly times are assets that AM can offer to Formula Student teams, for designing and manufacturing optimized structural parts. Additionally advancement of AM technologies provides opportunities to re-think design for manufacturing approach and take advantage of the unique capabilities of these technologies (2).
In this work, a redesign approach of a formula student car's structural component aiming to be manufactured utilising AM, is investigated. The design potential and guidelines for reduced weight and adequate stiffness are also included. Redesign is enhanced by the incorporation of topology optimization software tools such as ANSA and TOSCA. Finally FE analysis is performed before and after topology optimization in order to achieve equivalent stiffness for the redesigned part. Experimentation aspects of the final part due to the power based nature of the process are not examined in the current study.

2. CURRENT TRENDS OF DESIGNING AND MANUFACTURING APPROACHES IN FORMULA STUDENT

Stiffness of structural components in an FSAE car is of high importance. During design phase, upper limits for compliance of certain parts are set, due to the fact that these parts should preserve the desired characteristics when operating under load. Indicative examples are the suspension parts, which are of the most heavily loaded parts in a car. Stiffness is on highest priority so that to preserve the desired (designed) behaviour, in order for the car to maintain a stable dynamic behaviour. Higher-than-expected compliance in the suspension subsystem would lead to unexpected vehicle behaviour and lower performance. Moreover, total car mass is also a detrimental factor in vehicle performance. Thus, FSAE teams often reside to exotic materials or complicated designs in order to simultaneously satisfy those criteria. The most common approach implies parts milled out of a solid block of 7075 aerospace-grade aluminium. This approach is used by the majority of the competing teams; however design freedom is limited by the type of milling machine used and lead time and cost are usually high (5) (6). Moreover, this method does not allow the creation of 1-piece hollow structures that would give a great benefit in terms of stiffness-to-weight ratio. An alternative approach indicates using a 2-piece split design, consisting of two parts bonded together with structural adhesive (7). As promising as it might sound, this method requires extremely tight tolerances and control of the bonded surfaces. Moreover, heat developed during racing, significantly affects adhesive strength. A third solution involves the use of sheet metal, folded and welded together to fabricate the requested component (8). This method is cheap and allows creation of hollow structures with internal webs, however there is need for special fixtures during manufacturing. Moreover, heat induced by the welding torch causes wrapping of the parts, often requiring post-machining to keep the desired accuracy and tolerances and/or heat treatment to avoid residual stresses. A few teams over the last years have tried using hollow cast components (9). In that case the cost is usually high, as a side-effect of dedicated tooling required. Moreover, the casting process of lightweight alloys is often problematic; there is a certain minimum wall thickness for the process, which is usually too thick for FSAE parts, leading to higher weight. In addition, cast parts often experience porosity, leading to high scrap rate, thus further increasing lead time and cost.

Introduction of AM technology in FSAE: application and description of the design methodologies

A promising alternative to all aforementioned solutions is Additive Manufacturing. AM allows all the functionalities enabled by casting (hollow structures, internal webs etc.) but poses no limitations in minimum wall thickness, allows a defect-free manufacturing and requires no expensive and time-consuming dedicated tooling or fixtures. Moreover, the design freedom enabled by using AM can be further exploited for large weight gains.
When using AM, the designer can get away from feature-based design and move towards function-based design (10). Topology optimization is a relatively new field of study, which deals with the problem of finding the optimal distribution of material of a component based on specific criteria of performance or physical aspects (11). Topology optimization is widely used in AM applications due to its crucial role in the preliminary design conceptualization of a structural component (11). AM technology opens a new window for potential applications in an FSAE race car. Of utmost interest are suspension parts; here the high stiffness requirement is a matter of predictable handling, while weight savings are even more important, due to the fact that unsprung mass, whose oscillations should be controlled by the car spring/damper units, can be significantly reduced.

3. CASE STUDY DESCRIPTION: DESIGN & TOPOLOGY OPTIMIZATION PROCEDURE OF STRUCTURAL PART FOR AM

In this section, the procedure followed for the FE structural analysis and topology optimization of the investigated component is described. The structural part selected to demonstrate the potential of AM and topology optimization in that particular case study is a rear upright. The upright is a crucial component of every (race car) suspension system, due to the fact that all forces exerted to the vehicle during operation are transferred to the chassis through the uprights. The function of a vehicle upright is to provide a physical connection from the wheels to the suspension links and to provide mounting points for the installation of the brake caliper. Moreover, as this part is unsprung, reduction of its' mass is a very important aspect for every Formula Student team. The first approach (that was actually implemented on the UoP4e racecar (12)) aimed to meet the stiffness requirements set by the team while keeping the weight as low as possible. Moreover the design of the upright was restricted by the available manufacturing resources; therefore, the (geometrical) constraints of a 3-axis milling process were taken into account. Figure 1 shows the position of the upright in the car's wheel, as well as the initial design completed for milling operations.

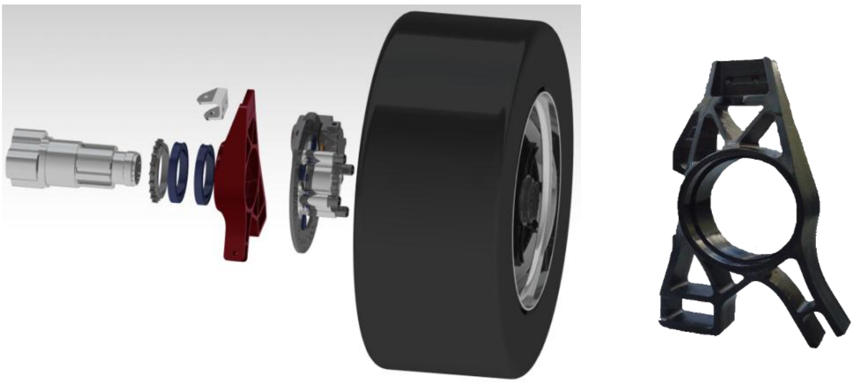

Figure 1 - Upright (red colour) position in the wheel (left), Rear Upright design (right)

Aluminium, steel and titanium are the materials considered as the most suitable alternatives for the particular component in Formula Student community. Aluminium 7075-T6 was the material selected in UoP4e, due to the low density compared to steel and the good manufacturing behaviour that presents in convectional subtractive processes compared to titanium (13).The loads and constraints for the FE and topology optimization analysis were specified. Cornering and braking forces were estimated using data from the cars' data acquisition system during competitions. The scenario that was selected to model the real conditions under which the upright operates is presented below.

Loads:

- Cornering force: 2943 N – Applied to the upper and lower holes surface (Figure 2). These points constitute the areas that the force is applied through the brackets of the wishbones.
- Braking force: 3230 N – Applied to the upper and lower holes surface (Figure 2). These points constitute the areas that the force is applied through the brackets of the wishbones.

Constraints:

- Fixed support constraint was applied in the bearings area (Figure 2).

The aforementioned modelling approach of the applied forces and constraints regarding the real working conditions of the upright were used in the next step; the topology optimization of the design.

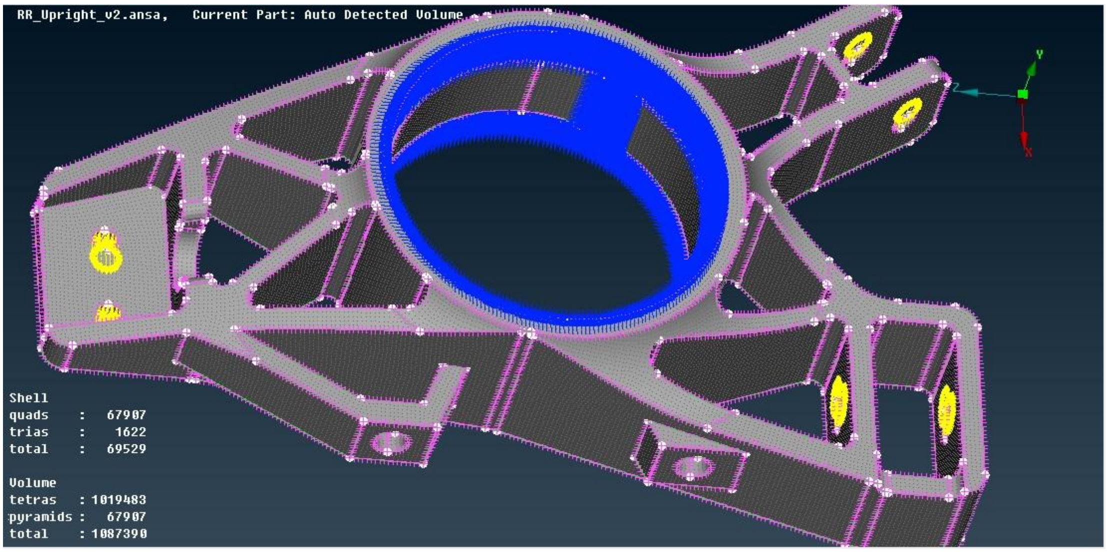

Figure 2 - Forces (yellow) applied on the surface of the holes – constraints applied on the bearings surface (blue)

Topology Optimization with ANSA-TOSCA software tool

In this work, topology optimization has been utilized in order to extract the optimal solution for the upright, providing at the same time maximized performance in terms of mass and cost reduction while maintaining the same targeted component stiffness. The TOSCA-ANSA environment (14) was chosen for the purposes of the current work and the procedure that was implemented is described below.

The first action before the initialization of optimization algorithm was the discretization of the investigated part. Meshing procedure can be performed inside ANSA environment either automatically or manually by letting the user decide the meshing parameters such as element type and size. The second approach was selected for the needs of this case study, aiming at more accurate and realistic results. The configuration of loads and constraints was the next input for TOSCA-ANSA environment in order to specify the algorithm the stresses on the component during the optimization process.

The definition of the design area is an important aspect during the configuration of a topology optimization analysis set up. In the particular field, the available part area for material reduction is specified. Consequently, several areas were excluded from the topology optimization analysis due to existing design and assembly constraints. The decision of the bearings dimensions is a multi-criteria choice and as a result the corresponding area could not be redesigned. Additionally, the wishbones mounting points of the upright could not be changed due to limitations created by the wishbones shape, fasteners dimensions and tooling accessibility. Brake calliper mounting points should be kept the same too, addressing the prerequisites of the calliper installation on the upright. Therefore, the areas highlighted in Figure 3 were selected for topology optimization analysis.

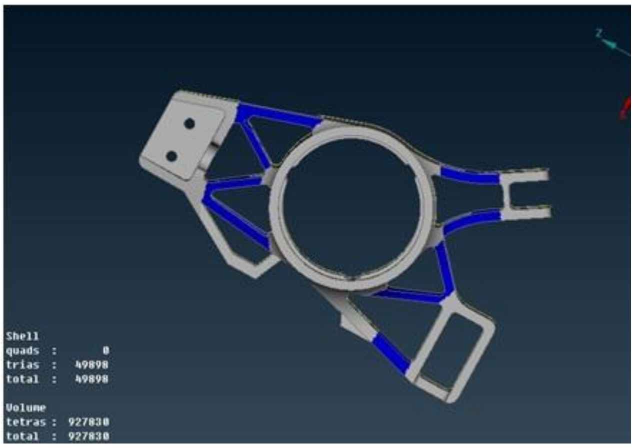

Figure 3 - Highlighted areas for topology optimization

In the next step, the objective function was established. TOSCA-ANSA environment offer a wide variety of available functions which depend on the results of the FE analysis. For this particular case study, the constraint of the total volume was selected as the performance criterion with which the algorithm would determine the material reduction from the design area. The decision for the aforementioned objective function was oriented by the fact that a reduction in the total volume while maintaining the same stresses level would lead to less material usage and therefore lower weight. After some iterations, the percentage of the removed volume was set at 57%. Using this value of removal rate, the aim of keeping the stresses at the same pre-optimized level could be achieved. Afterwards, the maximum number of iterations was defined and the output file for TOSCA was automatically created by ANSA. Finally, the analysis was ready to be initialized. TOSCA removed elements of the investigated areas and then the solver was enabled in order to calculate the results of the new design. The results were re-evaluated by TOSCA and another iteration initiated until the defined maximum number of iterations was satisfied.
The results of the topology optimization analysis are presented in the following section and a comparison between the milling and additive manufactured design approaches of the upright is performed. Moreover, the advantages of the recently fastest growing and promising AM process over convectional processes are summarized and further possible work on the particular case study in order the upright to be additively manufactured is suggested.

4. RESULTS & DISCUSSION

The outcome of the described topology optimization procedure is depicted in Figure 4. After the execution of the topology optimization algorithm the representation of the optimized upright is visualized. Following the topology optimization stage, it is usual to smooth the geometry to reduce the effects of the element boundaries and to convert the result into a mathematical CAD representation (15). However, in this work, after the identification of the possible material reduction areas, the redesign of the part was performed directly into the used design software package in order to be implemented afterwards in the solver.

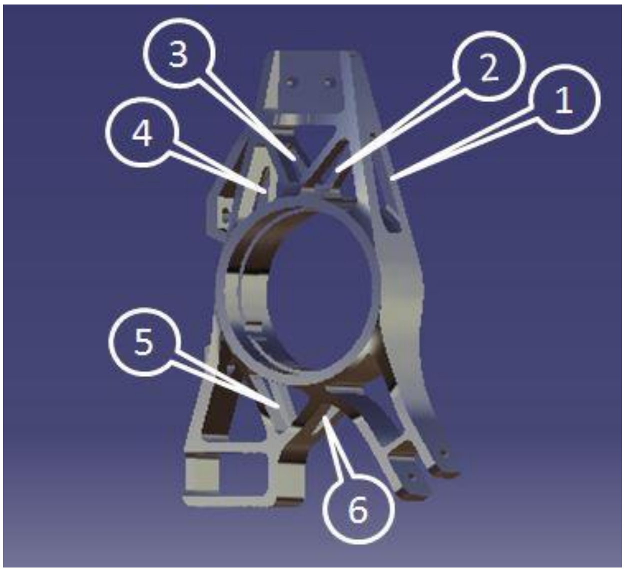

Figure 4 – Redesigned upright based on the topology optimization

Table 1 shows the weight and stiffness of the redesigned component before and after the topology optimization analysis. FE analysis performed for a combined (cornering and braking) worst case scenario which models the real operation conditions of the upright.

Part Description	Weight	Maximum Stress (MPa)	Deformations (mm)
Initial model	0,49 kg	202	0,357
Optimized model (57% volume reduction of the design area)	0,39 kg	250	0,37
Variation percentage	20,4 % reduction	23,7 % increase	3,6 % increase

Table 1- Comparative table between initial and optimized part in terms of weight and stiffness analysis values

From the table above it can be concluded that the level of the weight reduction is significant, especially when this is achieved for motorsport purposes. The performance potential due to the reduced weight is doubled because the particular design is implemented in both rear wheels of the car. Moreover an increase in the stresses and deformations can be noticed. However after the topology optimization the upright is more evenly loaded and the maximum stress value observed is lower than the aluminium's yield strength.
In conclusion the integration of topology optimization analysis in the design phase of AM process can lead in the creation of parts that are lighter and more durable (15). Combining the flexibility of the process, the freedom in design and the lack of specialized tooling that the convectional processes may use, AM present significant advantages in various production aspects. For the aims of the particular work a comparative table is cited below including production aspects of the upright for AM and milling approaches.

Additive Manufacturing Process	3-Axis CNC Milling Process
$AlSi_{10}Mg$ Aluminium powder	7075-T6 Aerospace Aluminium
Total Part Volume: 138,64 e^{-6} m^3	Total Part Volume: 173,3 e^{-6} m^3
Total Material used: 14 e^{-5} m^3	Total Material used: 28,8 e^{-5} m^3
Process Time: 5,2 h (approximately) (16)	Process Time: 8,5 h (approximately)
Mass: 0,39 kg	Mass: 0,49 kg

Table 2 - Comparison table of AM and milling production aspects for the investigated component

5. CONCLUSIONS

The current study demonstrates the potential enabled from use of AM technology in the substitution of conventional manufacturing methods used to manufacture parts of a FSAE racing car. It has been found that, at least for similar case studies, AM, when coupled with appropriate methodologies and software for structural analysis and topology optimization has great potential for lightweight and efficient production. Moreover, it is only logical to exploit topology optimization algorithms in conjunction with AM, shifting the design paradigm from feature-based to function-based.

For the particular case study presented, mechanical performance of the investigated component was significantly enhanced, by reducing mass by 100 grams. Albeit this seems rather small, it is a 20.4% reduction compared to the current (optimized) component, which is significant especially in highly demanding environments such as motorsport or aerospace. Moreover, this decrease in mass does not come in expense of overall component strength or stiffness. In addition to product performance, environmental performance of the production process is also better, at least in terms of raw material usage. It was found that in the case of Additively Manufacturing the part, less than half of the material is required when compared to traditional CNC milling process. Future work may include the investigation of lattice (or hollow) structures. The team aims into further investigate such technologies in future attempts, since presented technologies and methodologies will be highly applicable in the motorsport field for the years to come.

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