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DESIGN AND FE CALCULATIONS OF A LIGHTWEIGHT CIVIL UNMANNED AIR VEHICLE

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ABSTRACT

This script refers to the strategic design steps followed towards the scope of the structural optimization of an unmanned air vehicle (UAV). In order to attain the aforementioned aim, the strategy of parameterization has been followed, given the capabilities that modern computer aided design and engineering (CAD and CAE) programs provide to the aeronautical engineer. Accordingly, both the external shell structure and the internal structural parts of the aircraft have been interactively parameterized. The capability to parametrically amend the geometry and material properties of major and/or non-essential structural parts of the aircraft, allowed for several loop-like structural and aerodynamic analyses that led to significant airframe weight reduction of more than 30% between the initial-coarse and final-optimized structural configurations in a time effective manner. The outcome is a structurally integral aircraft according to the relevant Certification Specifications for Very Light Aeroplanes (CS-VLA) of the European Aviation Safety Agency (EASA).

Index Terms – Unmanned Air Vehicle, aeronautics, lightweight construction, parametric design, composite materials, finite element analyses.

1. INTRODUCTION

For the aeronautical engineer, the design of optimized aeronautical constructions could be regarded as a great challenge. Environmental [1] and financial [2], [3] issues are barely related to the intense need for lightweight aerostructures, whilst aviation organizations [4], [5] and aircraft certification specifications [6], imply the construction of safe and reliable flying machines. According to contemporary market and industrial demands, the balancing point between these contradictive needs that govern aircraft design should be attained into a strictly predefined time frame.

With regard to flying vehicles, optimization focuses on the following fields of interest; structural integrity in conjunction with airframe weight and aerodynamic performance. During structural optimization, the major scope to be attained is the maximum possible airframe weight reduction. Aircraft structure's weight lessening is attainable either through certain structural design amendments or by selection of proper materials, considering the stress field and the loading conditions on each area of the airframe, or through a combination of the abovementioned means. For civil applications (airliners, civil UAVs), aerodynamic optimization barely aims to total drag reduction, affecting flight endurance. Less structural weight and decreased drag means less fuel consumption and extended flying range. Such improved flying characteristics are of positive impact from both the financial and environmental points of view.

According to [7], [8], [9], [10], [11] and [12], aircraft design takes place in three phases, namely the conceptual, preliminary and detail design steps. During the conceptual design phase, major dimensions and flying characteristics of the aircraft are being determined in dependence on corresponding mission demands. For the UAV under investigation, these data are summarized in table 1. It is worth mentioning that in the framework of the relative project [13], a thorough economotechnical analysis of the UAV world market, including technical and financial data of more than 90 UAVs has been done. This action significantly contributed to the orientation of the design. Accordingly, both technical issues barely related to aerospace materials, airframe configurations, and electronic equipment applied on UAVs and financial aspects of UAV market have been analyzed. The aforementioned analysis pinpointed the importance of multilayered composites as major UAVs' structural material and provided an estimated weight reduction in comparison to a corresponding aerostructure made of aerospace metal alloys.

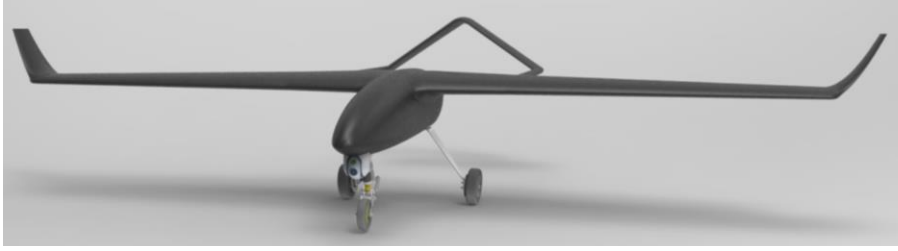


Fig. 1: Front-side view of the UAV

General UAV characteristics	
Wingspan	6m
Length	4,5m
Height	1,4m
Wing area	4,5m^2
Gross weight	181kg
Payload	35kg
Powerplant	1 X 30hp air-cooled internal combustion engine
UAV performance data	
Maximum speed	240km/h
Cruising speed	140km/h
Range	600km
Service ceiling	20000ft
Endurance	>10hrs
Maximum positive load factor	+4g
Maximum negative load factor	-2g

Table 1: General UAV characteristics and performance data

2. AIRFRAME PARAMETERIZATION

The accomplishment of the conceptual design phase resulted in a coarse configuration of the external shape of the aircraft. This initial-coarse shape has been used during preliminary design as guide for the determination of parameters that will be incorporated to the design of the

UAV's airframe. The aircraft is being divided into three main parts; fuselage, wing and tail. A series of corresponding parameters is being assigned for the external-shell structure and the internal structural parts of each major segment of the UAV. Two parameter categories could be distinguished; design parameters and parameters related to material properties. The design parameters refer either to the external – shell structure of the aircraft or its internal structural parts. Material parameters concern either the physical and mechanical material properties or the type and number of multilayered composites' layers and fiber orientation of carbon fiber laminates. The classification of the design parameters described above is depicted in *Figs 2* and *3*.

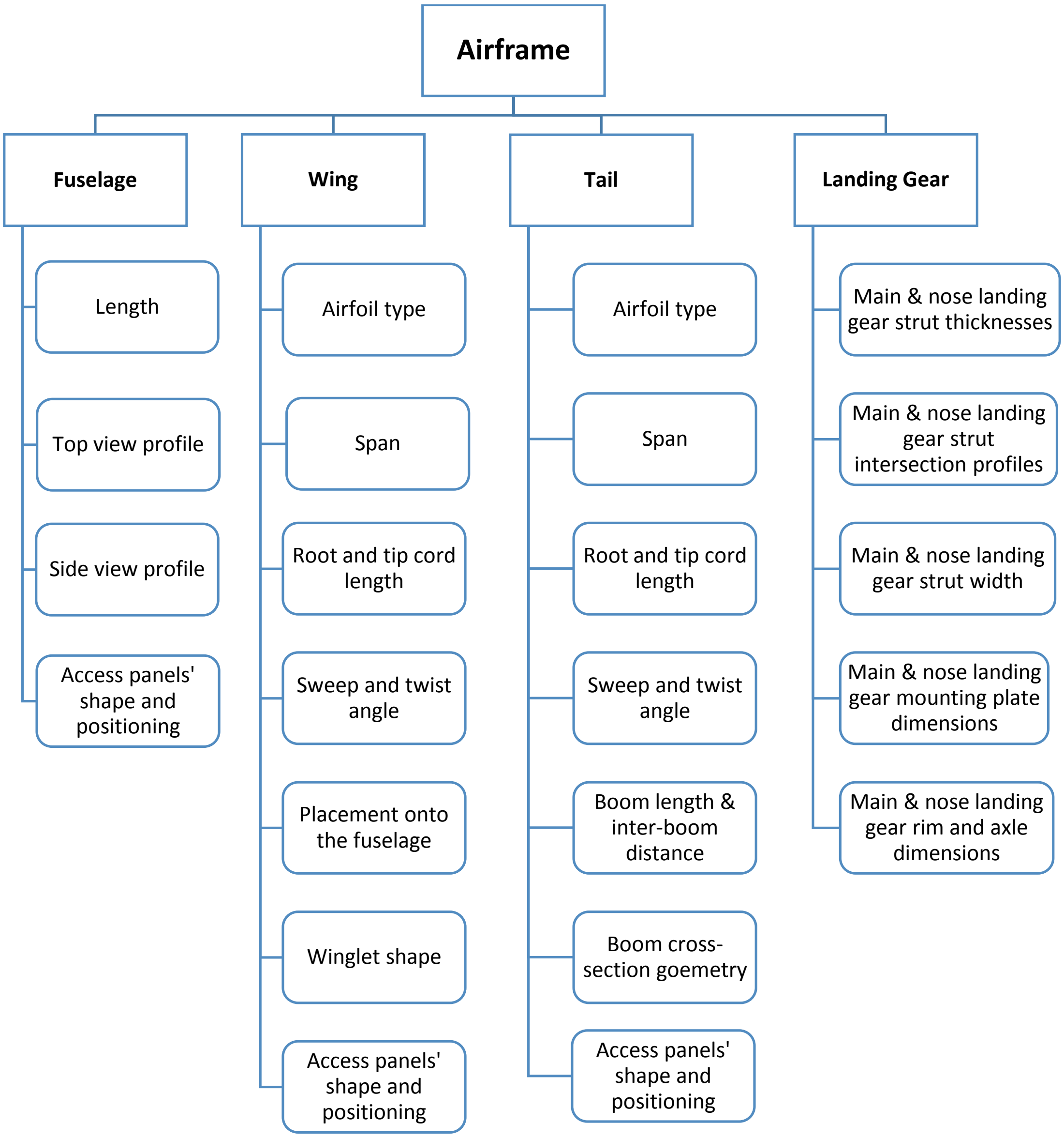


Fig. 2: *Parametrically controlled geometrical characteristics - external structure & landing gear*

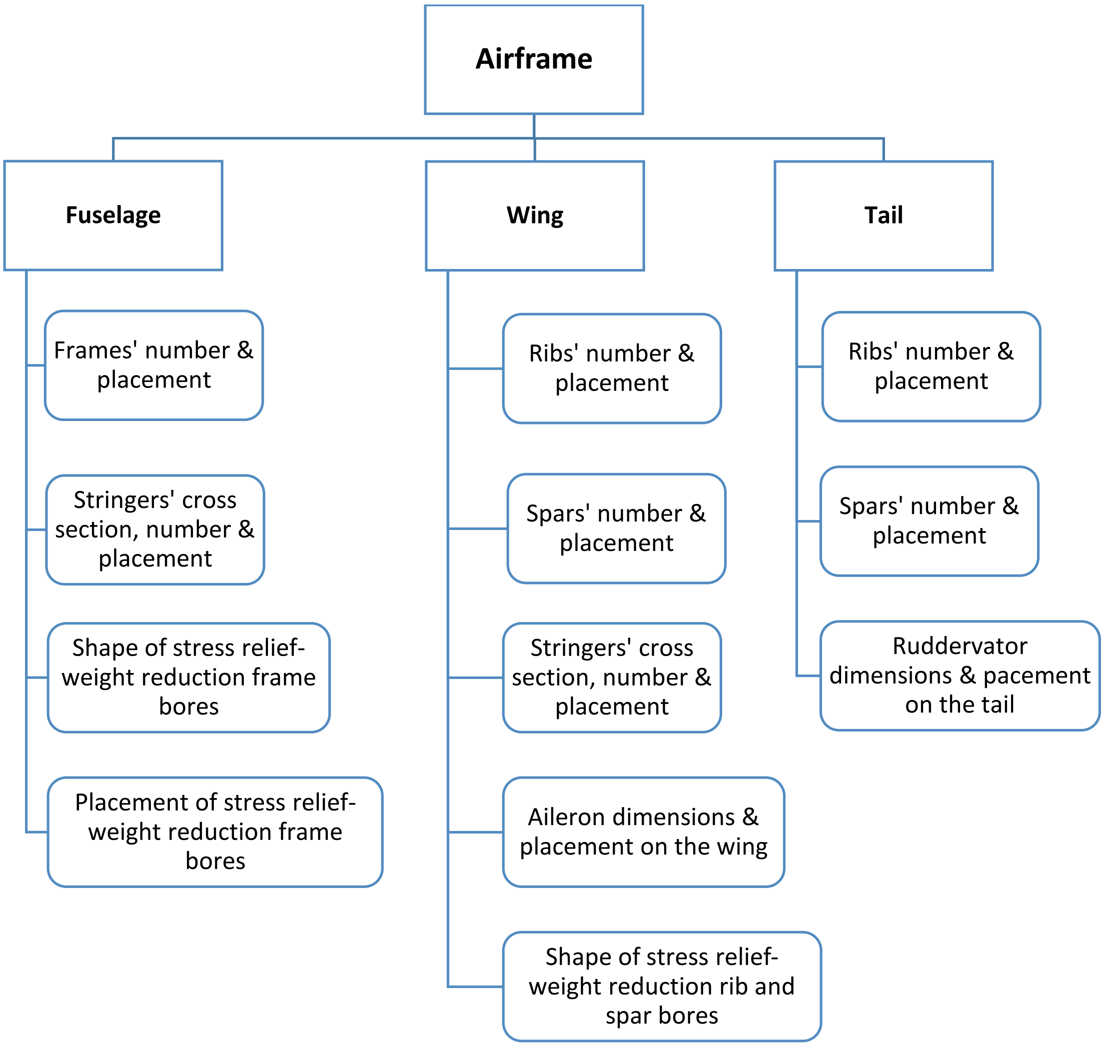


Fig 3: *Parametrically controlled geometrical characteristics – internal structural parts*

It is worth mentioning that the determination of parameters that affect the geometry of the UAV has been accomplished and "locked" during the preliminary design phase. These parameters where proven to be adequate for the structural optimization to be achieved.

In the case of material related parameters, they have been designated during the preliminary and detail design phases, merely due to the fact they are being assigned to the model into the environment of the corresponding CAE program, used for the implementation of the finite element analyses (FEA). Parameters related to engineering material properties refer to their physical and mechanical properties, type and number of layers of multilayered composites and fiber orientation of carbon fiber laminates.

3. FINITE ELEMET ANALYSIS

The numerical results derived from CFD analyses are not only used for the aerodynamic analysis (*Fig. 4*), i.e. lift and drag calculation and aerodynamic balancing of the aircraft, but they are also being transferred into the structural finite element model for the execution of certain structural analyses for several flight conditions (flight level, angle of attack (AoA), inertial loads, takeoff and landing conditions). The pressure field on the fluid (air of certain temperature and density, under atmospheric pressure conditions depending on the flight level) boundary domain is being transferred onto the shell structure of the UAV through a pressure mapping procedure that takes place into three interpolation attempts:

- Normal projection of the structural mesh nodes to the CFD mesh.
- If the first step fails, a node projection to the closest CFD mesh edge takes place.
- Lastly if the former step fails, each node of the external shell structure of the aircraft is being projected on the CFD face.

There are two options to implement the fluid-structure interaction capability (FSI) described above; the one-way FSI and the two-way FSI method, as extensively analysed in [14] and [15].

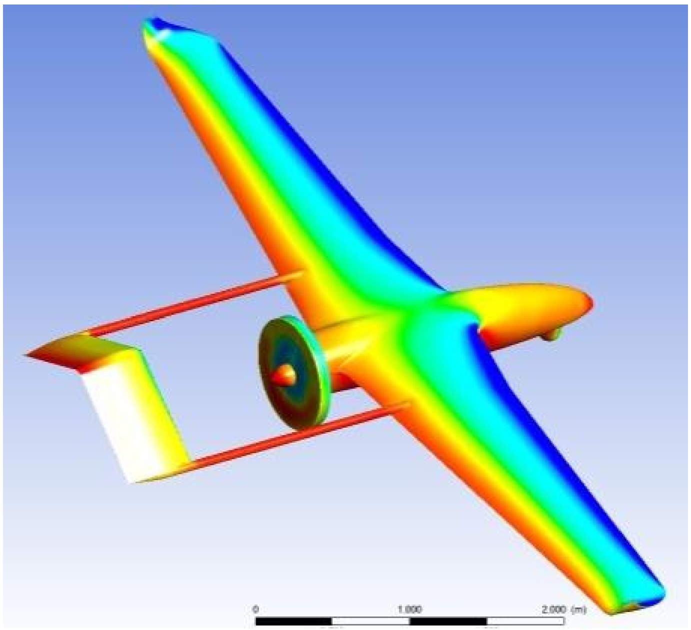


Fig. 4: *Pressure contour plot around the shell structure of the UAV, V=160km/h, h=10000ft, AoA=12°*

The investigated loading cases have been defined according to CS-VLA of EASA and the V-n diagram of the UAV determined through the preliminary design phase. The finite element structural analyses could be categorized as follows:

- FEA under combined aerodynamic and inertial loadings, during flight.
- FEA under inertial – terrain reaction loading, during landing and taxiing.

In order to model the UAV with finite elements, the whole structure has been divided into about 8000 surfaces. Then, certain surface groups have been defined to form corresponding named selections, either to help define a sole structural part of the aircraft or to allow for the definition of areas with the same structural characteristics (e.g. common thickness and/or same laminate configurations in the case of composites). In *Fig. 5*, such a group of surfaces located onto the lower wing skin is being highlighted. The material properties of this area (consisting of 84 surfaces) are parametrically controlled, allowing for thickness reduction of the corresponding shell surface till a lower permissible limit, which could be determined through a repetitive optimization loop. In *Fig. 6,* a discretization of the UAV's symmetrical section consisting of 361.219 shell elements is depicted.

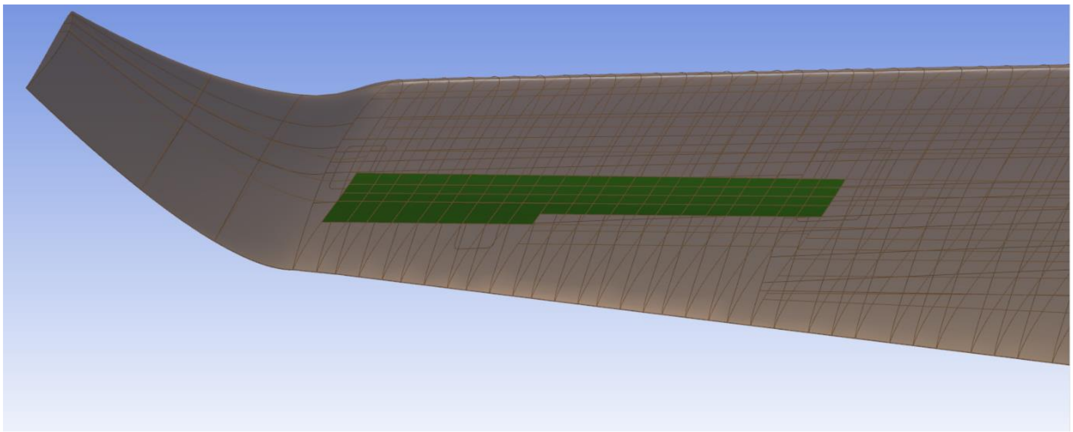


Fig. 5: *Group of 84 surfaces composing the corresponding lower wing skin named selection*

The FEA procedure has been implemented in two steps. Firstly, the structural integrity of the UAV has been obtained, i.e. airframe capable to withstand inertial loads for load factors up to 4.2 with a safety factor of 1.5. The aforementioned structural integrity has been achieved for two main construction options; structure made of aerospace alloys and airframe constructed of multi-layered composites, [16], [17], [18] and [19]. The comparison of the two UAV configurations quantified the prominent advantage of composites relative to aerospace aluminum alloys in terms of total airframe weight. Specifically, the total weight of the initial (structurally integral – not optimized) metallic configuration is 71kg, while the airframe of the corresponding version of the UAV if made of composites weights 52kg. This fact in conjunction with the conclusions derived from the corresponding economotechnical analysis described above, led to the selection of composites as major structural materials of the aircraft.

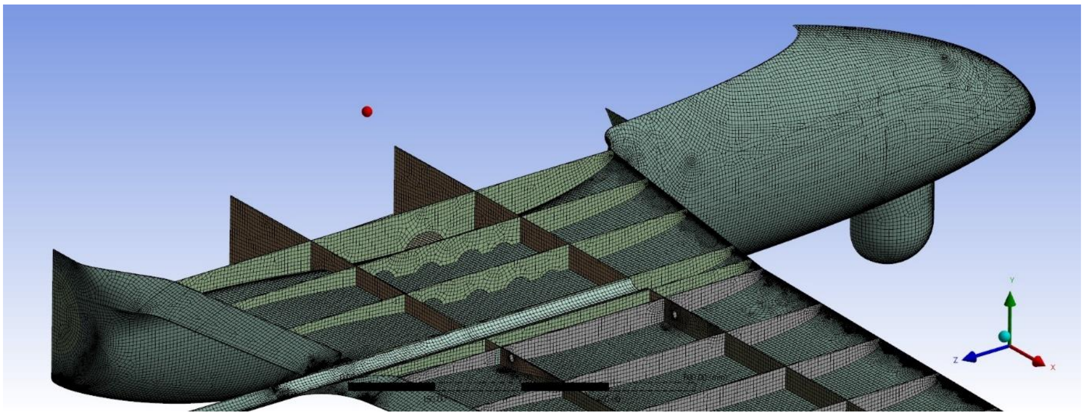


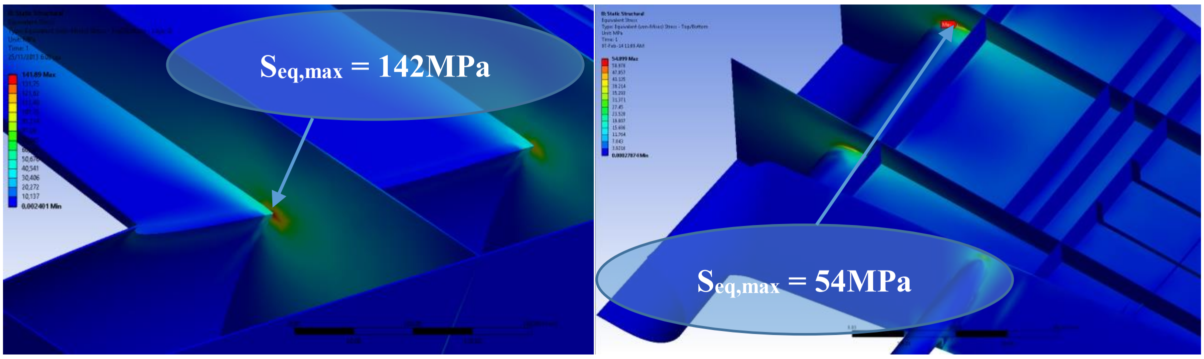
Fig. 6: *Cross section of the UAV, where part of the finite element mesh of the airframe, consisting of 361.219 shell elements is distinguishable (aluminum alloy 7075-T6 configuration)*

In a second step, towards the aim of airframe weight reduction, several optimization FEA took place, concerning the configuration (number and shape) of internal structural parts and composites (number of layers, type of laminates, thickness, and carbon fiber orientations). The optimization procedure is being implemented in three levels:

- Level 1: An initial improvement of the structural integrity of the aircraft on areas where immense stress values are being detected.
- Level 2: Alternations on the number and placement of internal structural parts of the aircraft, till the number of really needed parts is defined.

- Level 3: Sole or combined modifications on the number of layers, core thickness and orientation of multi-layered composites.

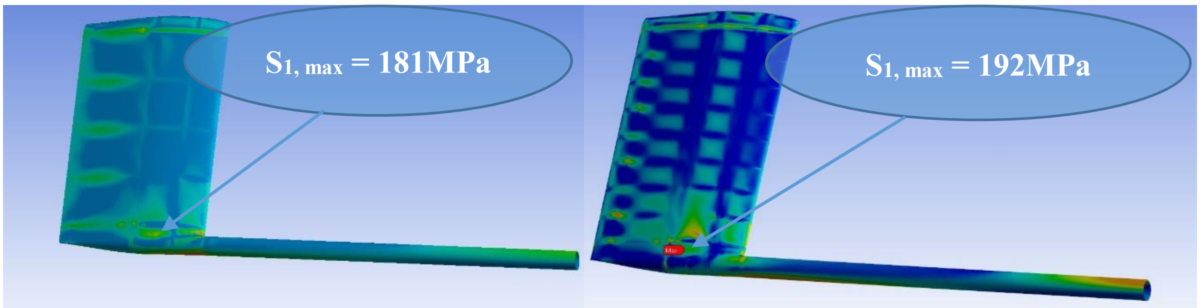
Combined alternations of parameters involved in optimization levels two (2) and three (3) were proven to efficiently contribute to further weight reduction of the airframe. A representative example of stress reduction on areas of stress concentration is depicted in *Fig 7*. It is prominent that the redesign of the geometrical configuration around the wing – fuselage joint area resulted in a significant stress reduction of more than 200%.



(a) ***(b)***

Fig. 7: ***(a)*** *Equivalent stress distribution on the wing root of the UAV corresponding to a structural configuration of sharp wing-fuselage matting, V=140km/h, h=10000ft, AoA=0°.* ***(b)*** *Equivalent stress distribution for the same flight conditions, after the redisign-smoothening of the wing-fuselage joint area*

An example of structural mass reduction refers to the empennage of the UAV as depicted in *Fig. 8*. Accordingly, a combined reduction of the boom and tail wing shell thicknesses in conjunction with increase of the number of tail ribs and decrease of the ribs' thickness, resulted in a noteworthy weight reduction of the empennage from 9kg to 6.2kg without unfavorable effect on its structural integrity.



(a) ***(b)***

Fig. 8: *First principal stress distribution on the UAV's empenge during rotation (critical takeoff phase), V=100km/h, h=0ft, maximum pitch rate.* ***(a)*** *Boom wall thickness=2mm, tail wing shell thickness =1,5mm, ribs' thickness=1,6mm, number of ribs=5, empennage mass=9kg,* ***(b)*** *Boom wall thickness= 1,5mm, tail wing shell thickness=0,8mm, ribs' thickness=1,2mm, number of ribs=9, empennage mass=6.2kg*

FEA optimization runs have been also done on the landing gear of the UAV. The non-retractable landing gear of the aircraft is made of aluminum alloy Al7075-T6, vastly used in aeronautical constructions due to its high ultimate, yield and fatigue strength (570Mpa, 505MPa and 159MPa respectively) and its better resistance under shock loads induced during hard landing or by foreign objects (stones and metallic parts on the runway during taxiing and landing, bird strikes etc.). As far as the main landing gear (MLG) is concerned the mass of the strut has been decreased from 4,5kg to 2,4kg per strut, leading to a total 4,2kg weight reduction. Three design steps of the main landing gear are shown in *Fig. 9*, where respective strut mass and maximum equivalent stress values for ideal landing conditions (smooth landing, load factor n=1) are being quoted.

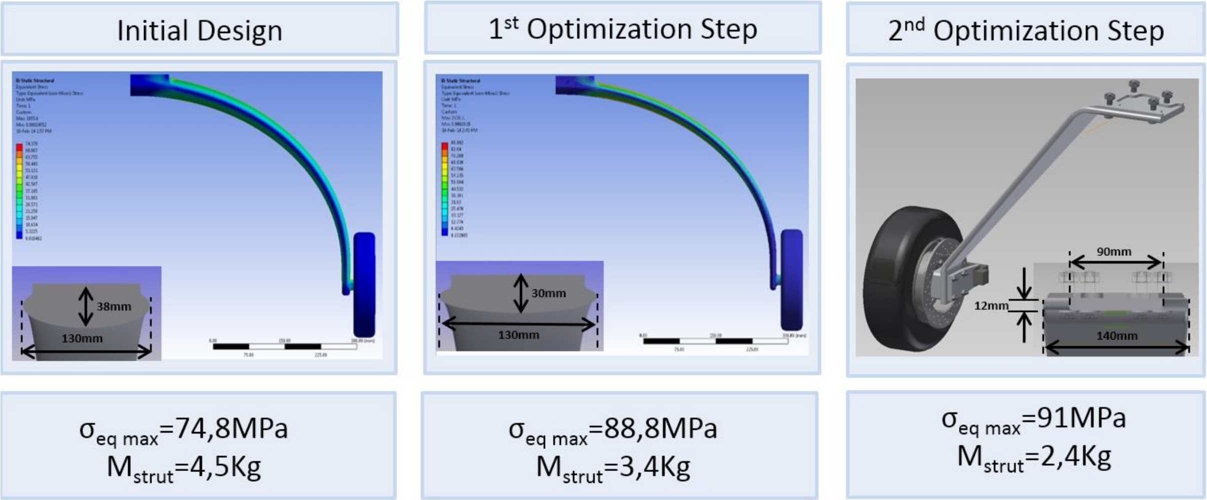


Fig. 9: *Main landing gear strut design steps, where strut intersections are distinguishable. Mass reduction between design steps is prominent, while the maximum equivalent stress values are well below the yield stress of the material (505MPa) in all three design configurations, for landing conditions where only MLG wheels touch the ground and load factor, n=1*

4. SUMMARY AND CONCLUSIONS

The design of parameterized engineering structures is a complex and time consuming procedure. Nevertheless, when the need of optimization becomes indispensable part of the design and analysis process, the time savings of the initial time and brain teasing effort to build parameterized structures is significant, as described herein. For the UAV under investigation, parameterization was proven to be one-way solution in order to obtain an aerodynamically and structurally optimized flying machine into a ten-month framework. Under proper strategic plan and provided a focused-adaptive to the problem manipulation of the vast capabilities of modern CAD and CAE software packages, aircraft design and optimization analysis were proven to be feasible in a time-effective manner. For the authors, one of the next tasks to be fulfilled is the interconnection of the data acquired by means of the aforementioned CAD and CAE tools with the production line, pursuing the challenge of building the aircraft taking advantage of computer aided manufacturing (CAM) technology.

5. AKNOWLEDGEMENTS

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