Comparative analysis of conventional and optimal methods for detail part design for light aircraft

A.O. Marinosyan[1] **and H. P. Panayotov**[2]

[1,2]Technical University – Sofia, Plovdiv Branch, Bulgaria

[1] sasho01@yahoo.com, [2] hristian@tu-plovdiv.bg

Abstract. The present paper evaluates the pros and cons of three different methods of detail design of parts for light aircraft: a conventional (heuristic) method, topology optimization and morphogenesis. This is done through applying these methods to solve the same design problem and analyze the results theoretically by means of finite element analysis under certain external loads. The theoretical results are compared to experimental using Digital Image Correlation (DIC) technique on real parts with the same loads applied. As a case study a control surface A-frame hinge similar to the lower rudder hinge of M-540 aircraft is considered.

1. Introduction

In the present study three different methods are used for light aircraft detail part design. In particular as a case study a typical control surface A-frame hinge is considered. Specifically the lower rudder hinge of M-540 light aircraft (Fig. 1, left) is examined. For light aircraft detail design usually heuristic and rational design is used, based on designer's experience rather than optimal design methods. Hence the aim of the study is a comparative analysis of conventional (non-optimal) and optimal design methods. Two different types of topology optimization methods are employed opposed to conventional design. The goal is to minimize the mass of the parts under same external loads mostly due to optimal material distribution. Additional constraints are imposed such as minimal displacements. In many cases topology optimization yields geometry that resembles natural shapes. Additive manufacturing such as 3D-printing is considered widely as a main method of production of optimal parts. The chosen design methods, both conventional and optimal are:

- Conventional. It is based on experience of skilled designers, and works on trial and error. Design organizations have accumulated that knowledge and distribute it to its employees as in-house design manuals. They provide allowables and guidelines for the design of different kinds of parts, as fittings, formers, ribs etc. Most times the proposed design has to be justified by simple stress calculations [3].

- Topology optimization. It may be divided into optimization problem formulation and running an optimization algorithm which suggests areas of material to be removed [2]. The solution requires additional initial and boundary conditions to be defined such as fixture, loading, material definition etc.

– Morphogenesis. It is basically another name of topological optimization, but the algorithm is capable of building structure by adding material within the design domain under pre-defined initial and boundary conditions [3],[4].

2. Detail design methods and part generation

For the abovementioned case study – A-frame part the used material is aluminum alloy with Young's modulus 7e+010 Pa, Poisson's ratio 0.346, density 2710 kg/m^3, yield strength 9.5e+007 Pa. This is a basic alloy, chosen to make possible both conventional and additive manufacturing of complex shaped parts. One load case is evaluated with two simultaneously applied perpendicular, in-plane forces at bearing hole. One with 1800N of magnitude, in plane, perpendicular to flight direction and one 180N of magnitude, in plane, parallel to the flight direction (Fig. 1, right.).

2.1. The *conventional part* was designed by heuristic approach and modeled using CATIA V5 CAD software by Dassault Systèmes®. The rationale behind the design is a strut-like structure for direct transfer of loads from the bearing hole to the attachment points – bolt holes. There is also a stabilizing connection between the struts, thus the name A-frame. The part has 8mm thickness allowance and was supposed to be fabricated by water jet cutting from 8mm thick raw plate (Fig. 1, right).

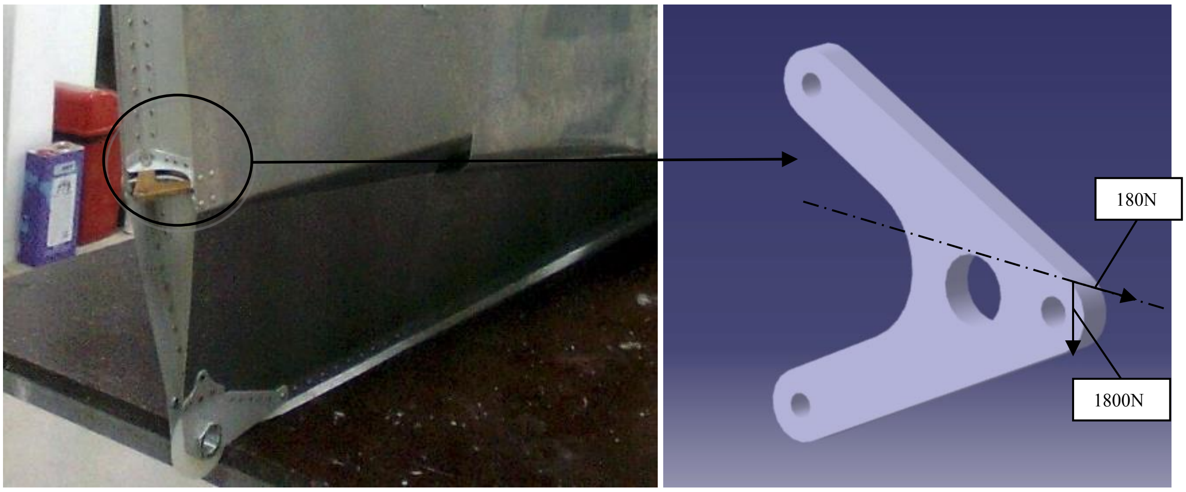


Figure 1. A-frame, generated by conventional approach

2.2. *Topology optimization* using Solid Works 2018 Topology Study software optimization module by Dassault Systèmes® was used to generate optimal part design. The algorithm removes under stressed material at certain external loads. The initial part has a triangular shape and allows the software to define the elements to be removed. The part is fixed to the attachment holes and the loads described are set (Fig. 2, left). The solver goal is Minimal mass with Displacement Constraint. In other words the Solid Works Topology study will try to find the stiffest structure possible given a certain amount of material removal. The final optimal part is generated and shown in the most right of Figure 2.

2.3. *Morphogenesis* using "Top 3D" MATLAB code by K. Liu. Topology optimization is a computational material distribution method for synthesizing structures without any preconceived shape. This freedom provides topology optimization with the ability to find innovative, high-performance structural layouts, which has attracted the interest of applied mathematicians and engineering designers. A topology optimization problem can be defined as a binary programming problem in which the objective is to find the distribution of material in a prescribed area or volume referred to as the *design domain*. A classical formulation, referred to as the *binary compliance problem*, is to find the "black and white" layout (i.e., solids and voids) that minimizes the work done by external forces (or compliance) subject to a volume constraint.

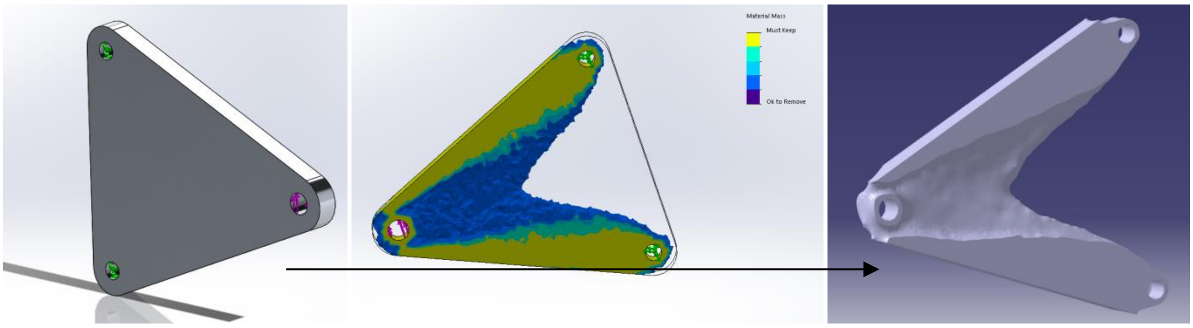


Figure 2. Topology-optimized A-frame generated in Solid Works

This code implements Sequential quadratic programming, Method of moving asymptote, and Optimality Criterion methods to the solution of the minimum compliance topology optimization problems. [4] The software requires definition of material properties and boundary conditions – fixtures and loads. Since there is not an option to define bolt fixture, the part is fixed at distributed zoned near the attachments, and the load is concentrated. The resulting part geometry form the solver (Fig. 3) can be exported in standard CAD-exchange formats. An obvious disadvantage of that product is low resolution of generated geometry.

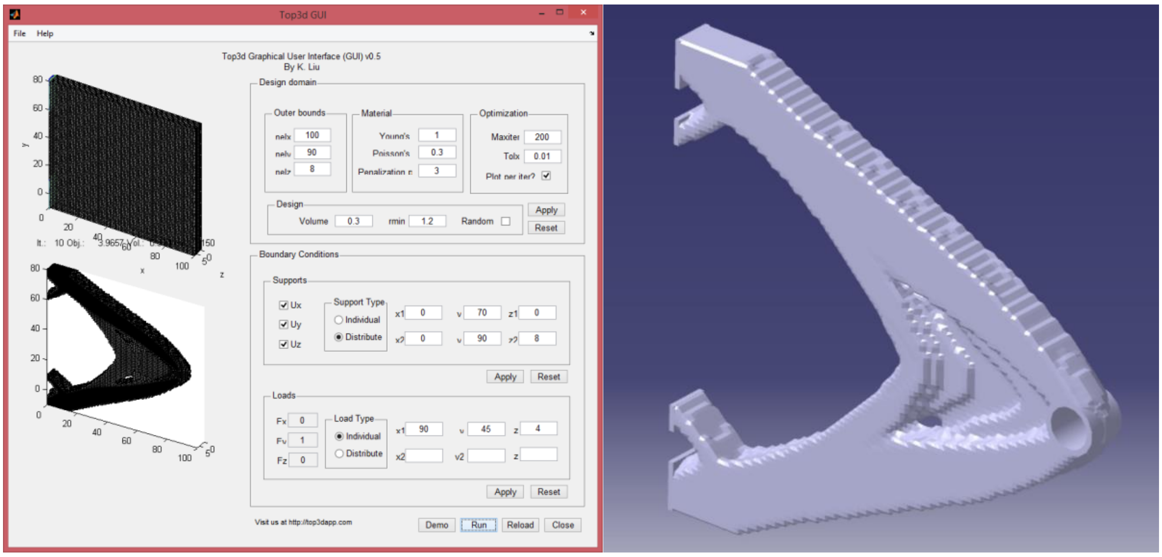
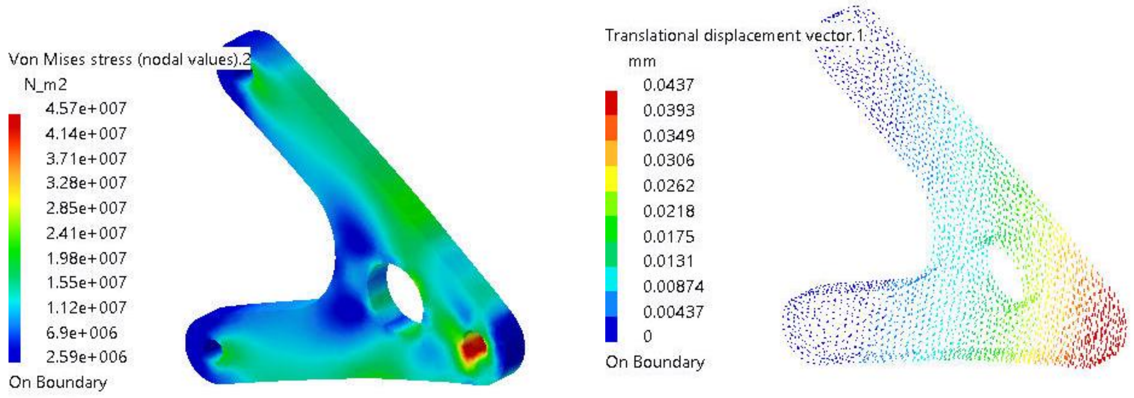


Figure 3. Morpho-generated A-frame by Top3D MATLAB optimizer

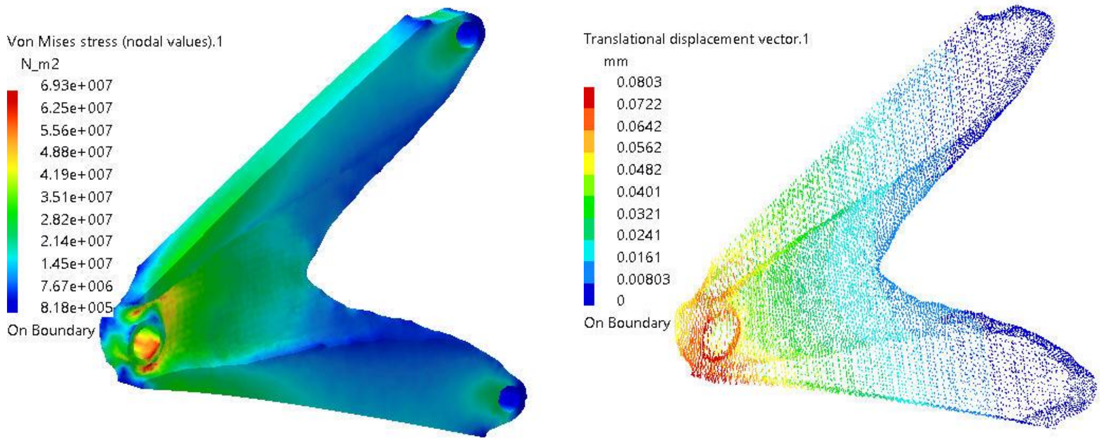
3. Finite element analysis

All parts are analysed purely theoretically in the Generative Part Structural Analysis module of CATIA V5 software tool using Finite Element Method (FEM) analysis. Since the topology optimization solvers do the synthesis of the parts it is appropriate to check the strength and stiffness of the designed parts using FEM analysis. The fixtures and loads shown on Fig. 1 are applied. The stress and displacement distributions are shown in Fig. 4 for all three parts.

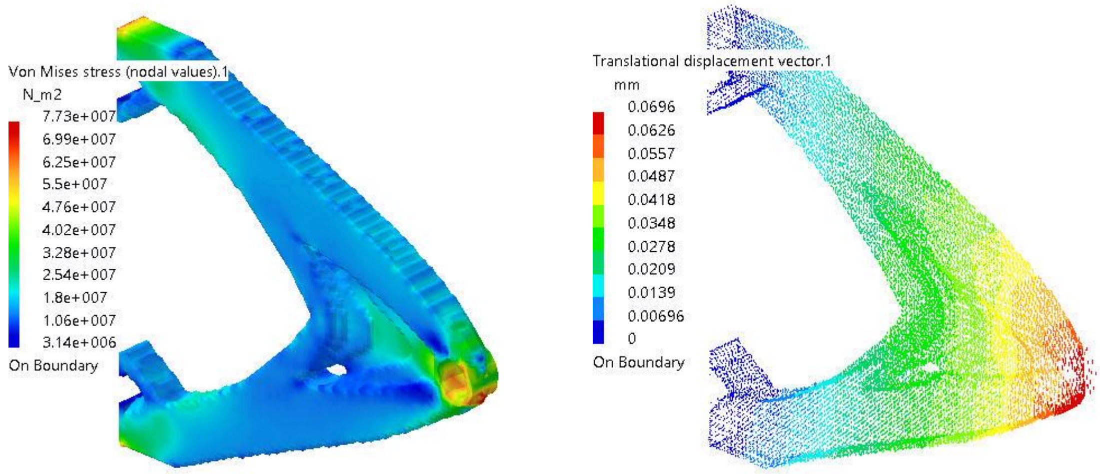
The conventional part has the lowest maximum stress magnitude and the smallest maximum displacements. It is obvious from the stress distribution (Fig 4a) that there are highly loaded zones of the part and zones with low stresses. One could go for another design iteration and manually remove the low-stressed zones.



a) Conventional part



b) Topology-optimized part



c) Morpho-generated part

Figure 4. Equivalent (von Mises) stresses (left) and displacements (right)

The optimal part, generated by Solid Works 2018 Topology Study application has greater magnitude of maximum stress and displacements than conventional part (Fig 4b). However it can be seen from the stress distributions that the maximal stresses are more evenly distributed at the “legs” of the A-frame. That is as a result of the optimizer. Nevertheless the stresses are concentrated at the loading mount.
The morpho-generated part has the biggest magnitude of maximum stress, but the maximum displacements are lower than Solid Works generated part (Fig. 4c). According to the colormap and the stress distribution it can be seen that the morpho-generated part has the most uniform stress distribution at satisfactory low displacements.

4. Experimental Digital Image Correlation (DIC) analysis

Digital Image Correlation (DIC) analysis is an experimental contactless, non-intrusive technique to determine displacement and strain distribution on deformed bodies. Two-dimensional (2-D) digital image correlation, which is used with a single camera, can measure only in-plane displacement/strain fields on plane objects. To overcome the drawback of 2-D digital image correlation, a 3-D digital image correlation technique, which combines digital image correlation with stereo vision and can measure the 3-D displacement field and surface strain field of 3-D object. The digital image correlation method uses the random speckle pattern to match the corresponding points precisely on two images [6]. The correlation of the corresponding points on the reference (non-deformed) and deformed image defines the displacement. In the present study 2D-DIC is used based on GOM Correlate software.
To determine experimentally the deformations of the designed parts a specially designed test stand is produced (Fig. 5). All three parts, conventional and optimal, are produced by milling and are shown on the right hand side in Fig. 6. The loads are generated by a hydraulic jack and read by a load cell. The resulting load is indicated on a monitor. The load case is the one described in Fig. 1. The loaded part is inclined at a certain angle (≈ 6°) to imitate both perpendicular forces at bearing hole.

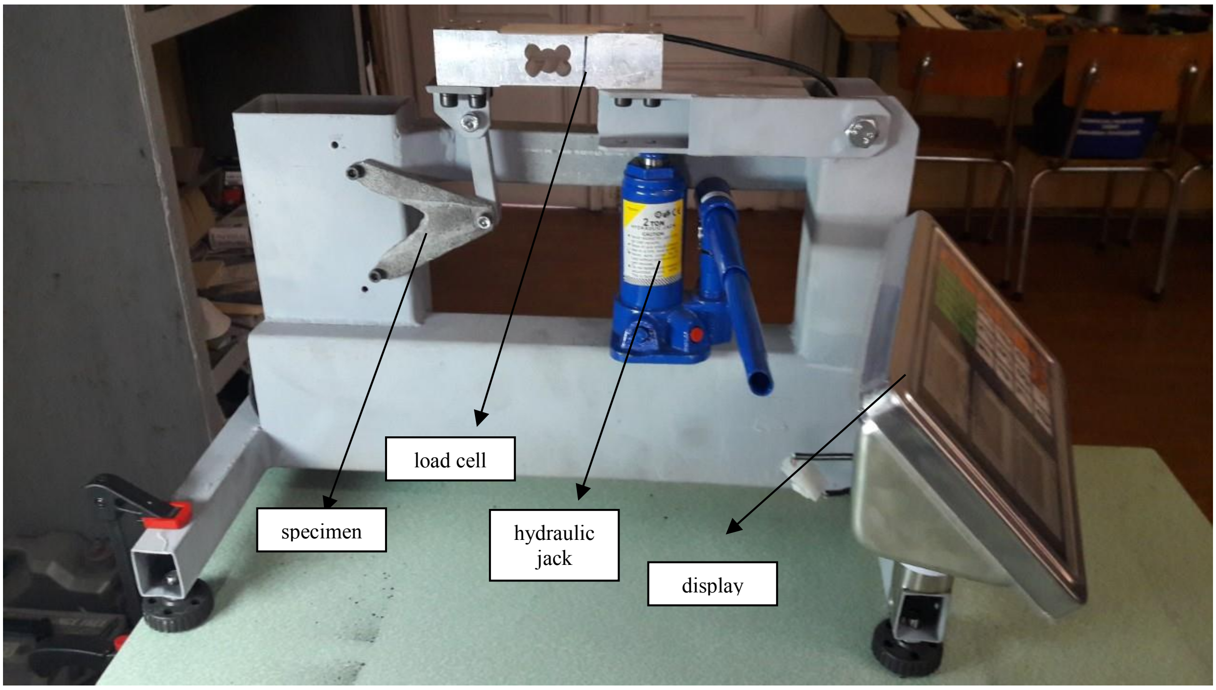
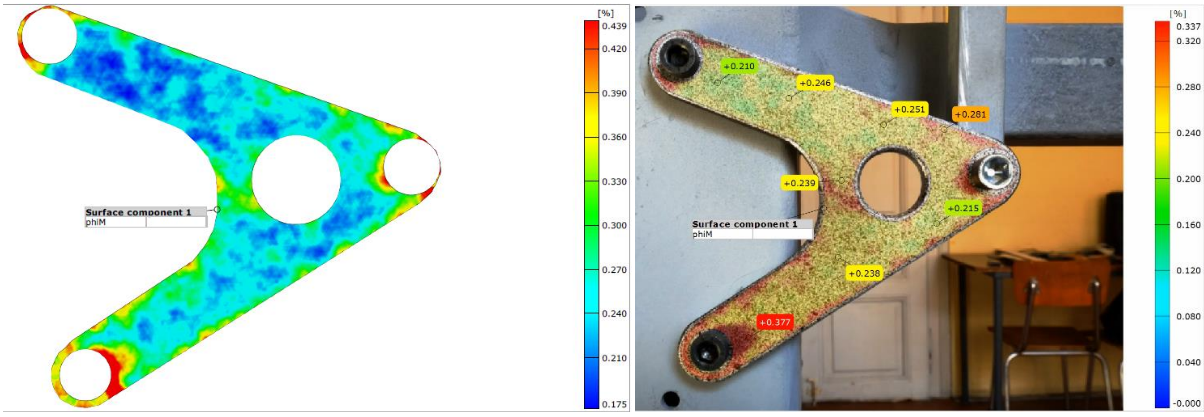
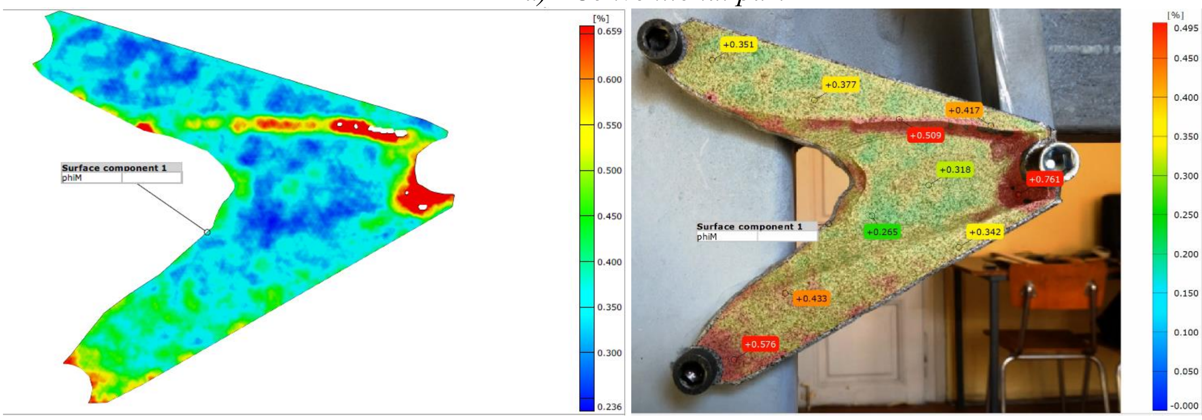


Figure 5. Experimental test stand

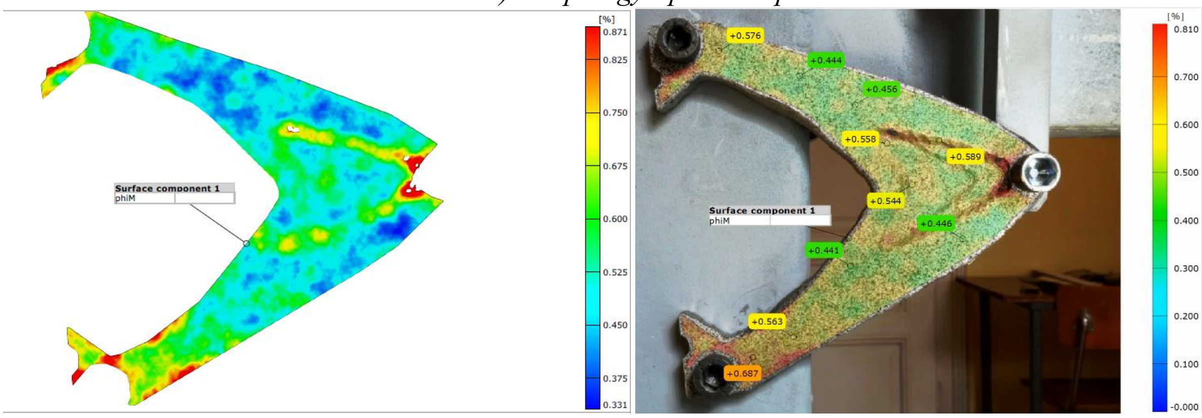
Figure 6 shows the experimental results using 2D-DIC technique on the designed parts.



a) Conventional part



a) Topology-optimized part



a) Morpho-generated part

Figure 6. Equivalent (von Mises) strains. Without (left) and with (right) original image

The displayed results are the equivalent (von Mises) strains [5]:

$$\varepsilon_{eq} = \frac{2}{3}\sqrt{\frac{3(e_{xx}^2+e_{yy}^2+e_{zz}^2)}{2}+\frac{3(\gamma_{xy}^2+\gamma_{yz}^2+\gamma_{zx}^2)}{4}}\,. \qquad (1)$$

With the deviatoric strains:

$$e_{xx} = +\frac{2}{3}\varepsilon_{xx} - \frac{1}{3}\varepsilon_{yy} - \frac{1}{3}\varepsilon_{zz}$$
$$e_{yy} = -\frac{1}{3}\varepsilon_{xx} + \frac{2}{3}\varepsilon_{yy} - \frac{1}{3}\varepsilon_{zz} \quad (2)$$
$$e_{zz} = -\frac{1}{3}\varepsilon_{xx} - \frac{1}{3}\varepsilon_{yy} + \frac{2}{3}\varepsilon_{zz}$$

The tensorial shear strain components of the infinitesimal strain tensor can then be expressed using the engineering strain definition, γ, as $\gamma_{ij} = 2\varepsilon_{ij}$. Finally for the strain tensor:

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{xy} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{yz} & \varepsilon_{zz} \end{bmatrix} = \begin{bmatrix} \varepsilon_{xx} & \frac{1}{2}\gamma_{xy} & \frac{1}{2}\gamma_{xz} \\ \frac{1}{2}\gamma_{xy} & \varepsilon_{yy} & \frac{1}{2}\gamma_{yz} \\ \frac{1}{2}\gamma_{zx} & \frac{1}{2}\gamma_{yz} & \varepsilon_{zz} \end{bmatrix}. \quad (3)$$

Results from Fig. 6 show similar loading and deformation to the simulation results (Fig. 4). The von Misses strains are connected to von Mises stresses by the elasticity moduli of the material. Again the maximum values of von Mises strains have the smallest magnitude for the conventional part, they are bigger for the topology-optimized part and the biggest value is for the morpho-generated part. The strain distribution on the part surface is more evenly distributed for the optimized parts. Concentration and increase of the equivalent strains are observed at the attachment and bearing holes. This confirms the simulation results.

5. Discussion and future work

Conventionally designed part has 77 grams of mass and 46 MPa peak von Mises stress. Topology-optimized part has 69 grams of mass, or 10% reduction over conventional and 70 MPa peak von Mises stress. The mass of morpho-generated part is 57 grams, or 26% reduction over conventional and 78 MPa peak von Mises stress.The reduced mass is of course important advantage of optimization based methods. They could provide lighter airframes with significant fuel savings during the lifespan of the airplane. The increased stress however, could mean shorter fatigue life and reduced overall damage tolerance. It may be preferable to use topology optimized parts at non fatigue critical locations where multiple load paths are present and assure adequate periodic inspections. Another concern for optimized parts is the complexity of production, which is a major factor in parts price.
The significance of theoretical results is somehow verified by real 2D-DIC deformation tests of the produced parts. However so far only initial analysis is made and further investigations are needed to accurately confirm simulation results. The proposed methods could be used in the future work for optimal design of more complex primary structure elements such as wing spar, ribs etc. [7]
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References

[1] Bendsøe MP, Sigmund O 2003 Topology optimization: theory, method and applications, Springer Verlag, ISBN 978-3-540-42992-0
[2] Doursat, R. 2008 Programmable architectures that are complex and self-organized: From morphogenesis to engineering. 11th International Conference on the Simulation and Synthesis of Living Systems (ALIFE XI), August 5-8, 2008, University of Southampton, Winchester, UK, pp. 181-188
[3] Aage N, Andreassen E, Lazarov BS, Sigmund O, 2017 Giga-voxel computational morphogenesis for structural design, *Nature*, vol **550**, no. 7674, pp. 84-86. DOI: 10.1038/nature23911
[4] Liu K, Tovar A 2014 An efficient 3D topology optimization code written in Matlab, Structural and Multidisciplinary Optimization **50**(6), ISSN: 1615-147X (Print) 1615-1488 (Online),

Springer Verlag, DOI: 10.1007/s00158-014-1107-x
[5] Equivalent Von Mises Strain https://dianafea.com/manuals/d944/Analys/node405.html
[6] Zheng-Zong Tang, Jin Liang et al. 2010 Three-dimentional digital image correlation system for deformation measurement in experimental mechanics, Optical Engineering **49**(10), 103601
[7] Marinov II 2010 The spar wing optimal design, Proceedings of scientific conference of National Military University, Dolna Mitropoliya, ISBN 978-954-713-094-4, pp. 36-38