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INCLUDING AEROELASTIC TAILORING IN THE CONCEPTUAL DESIGN PROCESS OF A COMPOSITE STRUT BRACED WING

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Keywords: *Aeroelasticity, Composite Materials, MDO, Conceptual Design*

Abstract

High aspect ratio strut braced aircraft can significantly reduce the induced drag. The inherent anisotropic behaviour of the composite material along with their weight saving potential can improve the performance of the aircraft during the flight. Thus, a composite strut braced aircraft is one of the promising candidates to achieve the targets set by European commission in Flightpath 2050 report. In this paper, multidisciplinary design analysis and optimization framework for strut braced aircrafts, is set-up involving tools provided by AGILE partners distributed worldwide. In the workflow, composite aeroelastic analysis and tailoring capability has been integrated with use of surrogate modelling. A design of experiment of the workflow with wing planform parameters as design variables is performed and a surrogate model is build. The optimization with an objective to reduce the fuel mass is performed using the surrogate of the workflow.

1 Introduction

The goals set out by the European Commission in the Flightpath 2050 report [1], include, among others, a 75% reduction in CO_2 emissions per passenger kilometer, 90% reduction in NOx and 60% reduction in perceived noise by 2050 as compared to the aircraft in the year 2000. These objectives do not seem to be realistic for conventional designs as it is becoming increasingly difficult to make the well-known wing and tube configuration more efficient. Advanced technologies along with novel design seems to have the potential to address the required leap in performance. One of the possible technologies to increase the efficiency of the aircraft is the application of composite materials. With high specific strength, the use of composite materials can be beneficial in terms of weight saving. A further advantage of the composite materials, is their inherent anisotropic behavior which can be tailored to achieve beneficial aeroelastic deformations and hence improved performance during the flight, thus providing a greater efficiency with a minimum weight penalty. With respect to unconventional designs, a strut braced wing with a high aspect ratio can significantly reduce the induced drag. The induced drag is one of the major contributors of the drag experienced by the aircraft during its entire mission. It accounts for about 30-40% of the airplane drag during the cruise and about 80-90% of the aircraft drag at low speeds [3]. A reduction in induced drag combined with saving in structural weight makes the composite strut braced aircraft as one of the promising candidates to achieve the required improvement in efficiency.

In the traditional design process, knowledge about the design increases, whereas the design freedom decreases as we go from conceptual to preliminary and finally to the detailed design as shown in Figure 1. In the case of conventional designs, the lack of knowledge during the initial stages is compensated through empirical knowledge. However, lack of such empirical knowledge for a novel design results in the need for increased physics based knowledge during the initial design process. The aircraft design process is inherently multidisciplinary and implementation of the Multidisciplinary Design and Optimization (MDO) techniques using the appropriate level of fidelity will help in achieving both increased freedom as well as increased knowledge in the design process.

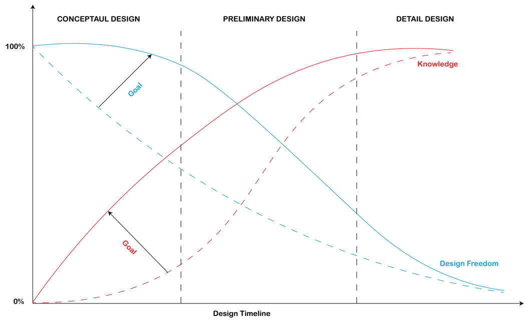


Fig. 1 : Trend of knowledge and freedom in aircraft design process [4].

Formulating a physics based MDO process is not a trivial task. There are two main challenges. First is to integrate disciplinary analysis modules which are distributed among different organizations, into a coherent distributed framework. Second is to integrate medium-high fidelity disciplinary tools in a computationally efficient manner. To support the formulation of collaborative, large-scale design and optimization frameworks, the AGILE [5] EU funded H2020 research project has formulated a novel design methodology, the so called AGILE Paradigm. The methodology of AGILE Paradigm is introduced in [6]. With the AGILE Paradigm, collaborative design and optimization frameworks for aircraft practiced by heterogeneous design teams, located multi-site, and with distributed expertise can be created in a coherent and consistent manner.

In this project, the AGILE paradigm is used to create a MDO framework for a composite strut braced wings. The focus of the current paper is on integrating the aeroelastic tailoring capabilities in the MDO of the composite strut braced wings.

2 MDO Framework

An extensive description of the collaborative MDO framework developed for strut braced wings is given in the companion paper [2]. For the sake of completeness, a brief overview of the formulated framework will be described. Figure 2 depicts the Multidisciplinary Design Analysis (MDA) workflow that is formulated to analyze the strut braced wing design. The tools used in the workflow are geographically distributed among various universities and research centers across Europe. The description of the different tools used is listed below

VAMPzero Conceptual design synthesizer based on the Top Level Aircraft Requirement (TLAR). Provided by DLR, Germany.

PROTEUS [7] Aeroelastic composite tailoring tool used to optimize the strut braced wing using composite materials. Provided by TU Delft, The Netherlands.

AMLoad Nastran based aeroelastic modelling tool used to obtain flexible aerodynamic polars. Provided by NLR, The Netherlands.

ASTRID [20] Designs the on-board subsystem architecture and calculates the system masses. Provided by Politecnico di Torino, Italy.

Engine Deck Evaluates, sizes and matches the Engine to the required performance. Provided by CIAM, Russian Federation

Mission Analysis Calculates the block fuel required for the given mission. Provided by DLR, Germany

FSI Calculates the static aeroelastic deformations using Computational fluid dynamics

(CFD). Provided by CFSE Engineering, Switzerland

The workflow is segregated into a Low Fidelity (LoFi) loop and a High Fidelity (HiFi) loop as can be seen in Figure 2. The aim of the LoFi loop is to get a converged design taking into account various disciplines provided by the respective modules. The converged design is fed to the HiFi aeroelastic chain which analysis the design and calculates the static aeroelastic polar. These polars are then used to correct the aeroelastic polars calculated in the LoFi loop using PROTEUS and AMLOAD. The LoFi analysis is performed with the corrected polars and then fed back to HiFi chain. The process continues till a converged solution is reached.

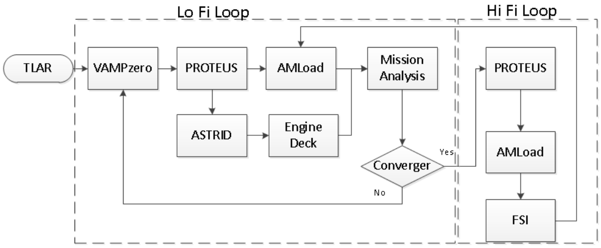


Fig. 2 : MDA Workflow.

2.1 PROTEUS

PROTEUS is an aeroelastic tool, developed at the Delft University of Technology. Figure 3 depicts the schematic representation of the framework of the PROTEUS. To start with, the wing is first divided into multiple spanwise sections, where each section is defined by laminates in the chord wise direction. The cross sectional modeller uses the laminate properties and the cross-sectional geometry to generate the Timoshenko cross-sectional stiffness matrices. A non linear aeroelastic analysis is carried out for multiple load cases by coupling the geometrically nonlinear Timoshenko beam model to a vortex lattice aerodynamic model. A linearized dynamic aeroelastic analysis is carried out around the nonlinear static equilibrium solution. In the post processing, the cross sectional modeller is used to retrieve the strains in the three-dimensional wing structure. Based on the applied strains in the structure, strength and buckling properties of the wing are calculated and fed to the optimizer as constraints. Since, analytical derivatives of the objective and constraints with respect to the design variable are calculated with PROTEUS, the gradient based optimizer, Globally Convergent Method of Moving Asymptotes (GCMMA) [13] is used for optimization. A detailed description of the PROTEUS is given in work by Werter and De Breuker [7].

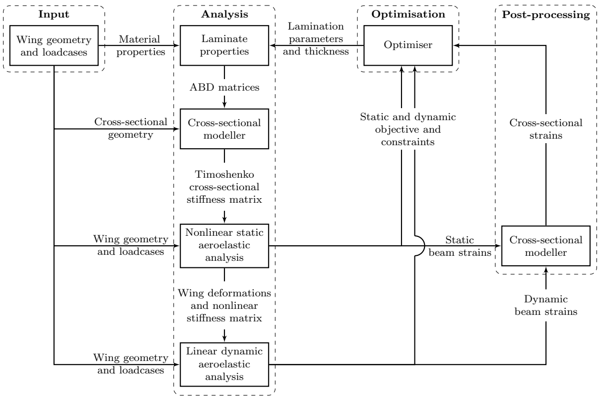


Fig. 3 : Framework of PROTEUS [7].

2.2 AMLoad

AMLoad, developed by the Netherlands Aerospace Centre (NLR), is a methodology for fast aeroelastic modelling and loads/flutter analyses. This methodology allows for an estimation of aerodynamic performance and design loads on aerodynamic aircraft components, including control surfaces, with little available input typical for a conceptual design stage. AMLoad provides the designer with more insight into the effect of design changes and thereby mitigates the risk of large modifications in the next design phases. It also increases the knowledge of design changes such that more detailed feedback can be provided to the original equipment manufacturer.

2.3 Aeroelastic Chain

The aeroelastic chain starts with PROTEUS, in which the stiffness and thickness optimization of the wing structure described in the CPACS file is

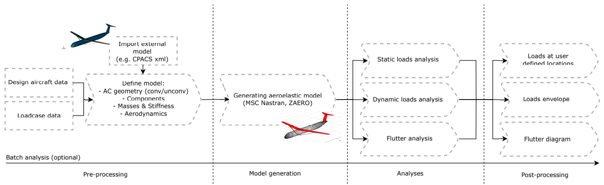


Fig. 4 : Framework of AMLoad.

carried out. The material properties used for optimization is given in Table 1. The optimization problem is shown in Table 2. The objective of the study is to minimize the structural weight of the wing. The wing is divided into 8 sections; 7 sections along the spanwise direction and 1 section representing the strut. Each spanwise section has one laminate in the chord-wise direction. This results in 31 unique laminates. Laminates are symmetric and unbalanced. Every laminate is described by eight lamination parameters and one thickness variable, resulting in a total of 279 design variables.

Table 1: Material Properties of AS4/3506.

Property	**Value** (GPa)
E_{11}	147
E_{22}	10.3
G_{12}	7
ν_{12}	0.27
X_t	2.28
X_c	1.72
Y_t	0.057
Y_c	0.23
S	0.076

To ensure that lamination parameters represent a realistic ply distribution, feasibility equations formulated by Hammer et al. [14], Raju et al. [15] and Wu et al. [16] are applied. The modified Tsai Wu failure envelope [17] suitable for lamination parameter domain is used to assess the static strength of the laminate. The stability of the panel in buckling is based on idealized buckling model formulated by Dillinger et al. [18]. To guarantee the static and dynamic aeroelastic stability of the wing, the real part of the eigenvalues of the state matrix should be less than zero. The local angle of attack is constrained to a maximum of 12 degrees and a minimum of -12 degrees.

Table 3 gives the information on the loadcases which are used for the current study. These loadcases, represent the flutter boundary, 2.5g symmetric pull up maneuver and -1g symmetric push down maneuver.

The properties of the optimized wing structure is exported to the CPACS file and forwarded to AMLoad. In AMLoad, a conversion script is used to convert the CPACS input parameters to AMLoad's required input variables. The framework for integrating PROTEUS with AMLoad is shown in Figure 5. In the last step before the analyses, the generated structural model for the wing and strut is replaced by the optimized stiffness and mass matrices obtained from PROTEUS. The other components are modelled by means of beam structural elements and are relatively stiff. The structural matrices are included in the MSC Nastran model by means of Direct Matrix Inputs at Points (DMIG) cards [8, 9].

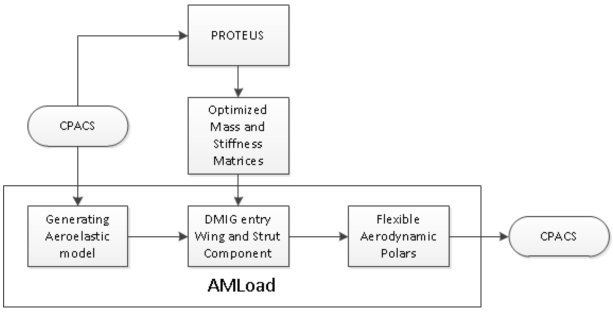


Fig. 5 : Workflow to generate the flexible polars using AMLoad and PROTEUS.

Since AMLoad is based on panel aerodynamics (Vortex Lattice Method (VLM)) only the Induced Drag (C_{D_i}) component is obtained as a function of the Lift Coefficient (C_L). The total Parasite Drag (C_{D_0}) is obtained using the methods described in [10]. Within the VLM method, the aerodynamic panels are corrected for the airfoil camber specified in the CPACS input file. The full aircraft aerodynamic model is presented in Figure 6. Static aeroelastic analysis is done using the modal approach, meaning the structural displacements due to the external aerodynamic

Table 2: Optimization Setup.

Type	**Parameter**	**# responses**
Objective	Minimize Wing Mass	1
Design Variables	Lamination Parameter Laminate Thickness	279
Constraints	Laminate Feasibility	140
	Static Strength	384/loadcase
	Buckling	1792/loadcase
	Aeroelastic Stability	10/loadcase
	Local Angle of Attack	22/loadcase

Table 3: List of Loadcases.

Loadcase ID	**V** (m/s)	**Altitude** (m)	**Load Factor**
1	264	11,000	1
2	230	11,000	2.5
3	230	11,000	-1

loading are expressed as a linear combination of the main modes. Within the analyses the first 25 elastic modes are included. The structural and aerodynamic models are splined and the static aeroelastic analyses are done for a combination of Mach and Angle of Attack (AoA) to determine the flexible polars as is shown in Figure 7.

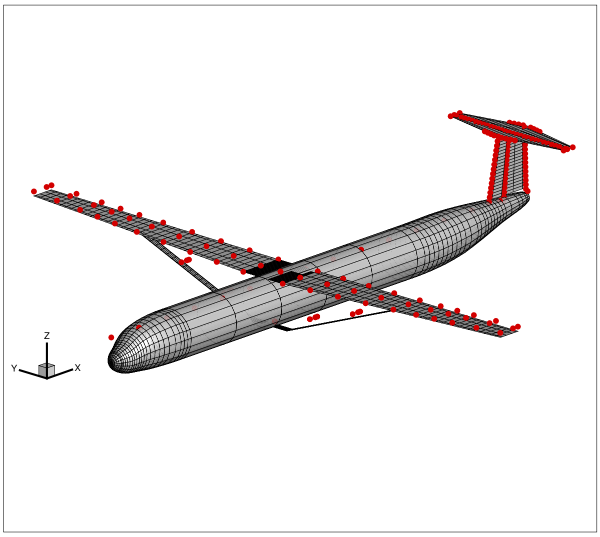


Fig. 6 : Full aircraft aerodynamic model including spline points (red).

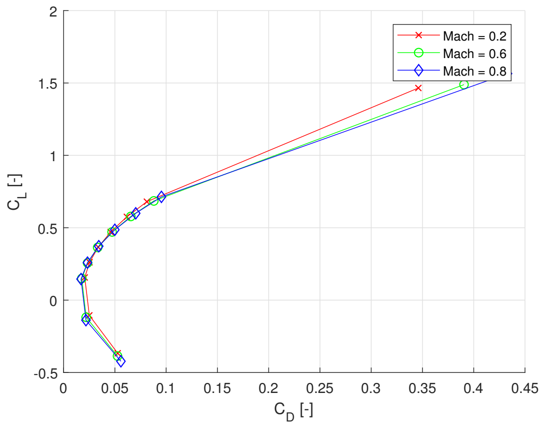


Fig. 7 : Flexible aerodynamic polar for different Mach numbers.

3 Surrogate Modelling

Compared to the other tools in the LoFi loop depicted in the Figure 2, PROTEUS is computationally a bit more expensive as there is an optimization process of entire wing structure involved. As a result including PROTEUS is not a feasible option in the workflow for the conceptual design process. An alternative is to use a surrogate model of PROTEUS. PROTEUS is used in two ways in the workflow; first is to get a tailored wing and strut structural mass satisfying all the constraints specified in Table 2, second to provide optimized stiffness and mass matrices to AMLoad which will calculate the flexible polars. Thus 2 surrogate models are created. One with PROTEUS and one a combination of PROTEUS and AMLoad.

3.1 PROTEUS Surrogate

For the surrogate model of PROTEUS, Table 4 describes the input and output parameters. To build the surrogate, a Design of Experiments (DOE) of 70 points is created using the Latin Hypercube Sampling (LHS) strategy. At each of the 70 points, stiffness and thickness optimization of the wing structure is performed. For the 8 points out of 70, a feasible solution could not be reached. Hence, the surrogate model is built using the remaining 62 points. 3 methods were used to create the surrogate model; Kriging model with exponential correlation function (Krigexp), Kriging model with cubic correlation function (Krigcub) and 2nd order polynomial regression (Poly2). The Root Mean Square Error (RMSE) using the k-fold cross-validation method for the 3 outputs is shown in Table 5. Krigexp seems to provide the best fit for the wing and strut mass whereas Krigcub is the best fit for flutter speed. With 62 sample points for 7 input variables, the RMSE for the wing and strut mass is on an acceptable level. However, the flutter speed has a RMSE of 74 m/s which is high. More investigation needs to be done on creating a surrogate model which has a better prediction for flutter speed or by increasing the number of design points needed to build the surrogate.

Table 4: Description of input and output variables for PROTEUS surrogate model.

Input Variables	**Bounds**	**Units**
Aspect ratio (AR)	12-21	-
Sweep	15-25	degree
Span	28-42	m
Strut t/c	0.09-0.15	-
Wing t/c	0.09-0.15	-
Strut location	0.5-0.75	-
Maximum takeoff mass	38,000-50,000	kg
Output Variables		
Wing mass		
Strut Mass		
Flutter Velocity		

Table 5: RMSE for the output of PROTEUS surrogate model.

Output Parameter	**Krigcub**	**Krigexp**	**Poly2**
Wing Mass	285 kg	216 kg	220 kg
Strut Mass	139 kg	124 kg	379 kg
Flutter Velocity	73.2 m/s	74.4 m/s	98.2 m/s

3.2 AMLoad Surrogate

The optimized stiffness and mass matrices for the feasible 62 points in the DOE sample calculated by PROTEUS is fed to AMLoad. For the surrogate of AMLoad, in addition to the input variables used to create surrogate of PROTEUS, each design point is evaluated for a range of Mach numbers and AoA to calculate the aero performance map. This map is used by the mission analysis tool to calculate the required fuel for the given mission. Table 6 describes the input and output parameters for the AMLoad surrogate. To create the surrogate, 2232 samples (62 cases, 4 Mach numbers and 9 AoA) are used. For each sample, the aerodynamic coefficients; Coefficient of Force in x Direction (C_{fx}), Coefficient of Force in z Direction (C_{fz}) and Coefficient of Moment in y Direction (C_{my}) are calculated. NLR's surrogate modelling tool MultiFit [19] is used for fitting the data set. MultiFit is a MATLAB based tool that integrates several fitting techniques either based on data interpolation (e.g. spline, kriging) or approximation (e.g. polynomials, neural networks, radial basis functions).

Four different fits methods have been evaluated for the creation of the surrogate; Artificial Neural Network (ANN), Radial Basis Function (RBF), Poly2 and a Combination of the Polynomial with a Generalized Linear Model Regression (Poly-glm). To check the accuracy of the different methods, k-fold cross-validation method was used. Table 7 provides the description of the RMSE for the different fit methods.

The ANN seems to provide the best fit result. Fits based on this method have been further optimized using the Neural Network toolbox, in combination with Bayesian Regularization (to avoid overfitting). ANNs have been applied with one

Table 6: Description of input and output variables for AMLoad surrogate model.

Input Variables	Bounds	Units
AR	12-21	-
Sweep	15-25	degree
Span	28-42	m
Strut t/c	0.09-0.15	-
Wing t/c	0.09-0.15	-
Strut location	0.5-0.75	-
Maximum takeoff mass	38,000-50,000	kg
Mach number	0.2-0.8	-
AoA	-5-12.5	degree
Output Variables		
C_{fx}		
C_{fz}		
C_{my}		

hidden layer consisting of 12, 12 and 8 hidden neurons for C_{fx}, C_{fz} and C_{my} respectively. C_{fz} and C_{my} have larger prediction errors than C_{fx}. Additional designs could be evaluated with PROTEUS/AMLoad for improving the accuracy of the surrogate model.

4 HiFi Aeroelastic Chain

The optimized design from the low fidelity block of the workflow will then be analyzed with a HiFi aeroelastic chain. In this chain, along with PROTEUS and AMLoad, high fidelity Fluid Structure Interaction (FSI) simulations will be performed by CFSE Engineering [11]. CFSE uses the Navier-Stokes Multi-Block (NSMB) CFD solver using the cell-centered finite volume method on multi-block structured grids. The structural model is solved using the tool B2000 from SMR Engineering and Development [12]. One of the inputs that can be imported in B2000 is a modal analysis from MSC Nastran.

The optimized design obtained from the surrogate based LoFi workflow is fed to PROTEUS. PROTEUS performs a stiffness and thickness optimization of the wing and the strut structure using the materials given in Table 1. The optimized stiffness and mass matrices is then fed to AMLoad in which a full aircraft MSC Nastran structural model is made in which the wing and strut are represented by matrices. This inherently means that the detailed finite element properties are non-existing anymore but captured in those matrices. However, in order to perform high fidelity aeroelastic simulations, a 3D structural model is required in order to spline the model to the CFD mesh. For this purpose, the simplified structural MSC Nastran model (existing of nodes in combination with the DMIG cards) is extended using Rigid Body Element (RBE2). The RBE2 element is a rigid body connected to an arbitrary number of grid points. In this case, the structural nodes which include the structural dynamic matrices are connected to surrounding grid points representing the box structure of the wing (see Figure 8 and 9). The independent degrees of freedom of the surrounding nodes are the six components of motion at a single grid point. A restriction of using the rigid elements is the fact that local modes, e.g. local buckling modes or wing torsion at a specified spanwise location, cannot be captured accurately. However, these kind of local modes do not influence the aeroelastic simulation and therefore do not compromise the results. Figure 10 shows a strut bending in combination with a wing bending mode splined to the CFD model.

Using the proposed chain, the results from the HiFi aeroelastic simulation will be used to update the flexible polars in the LoFi workflow.

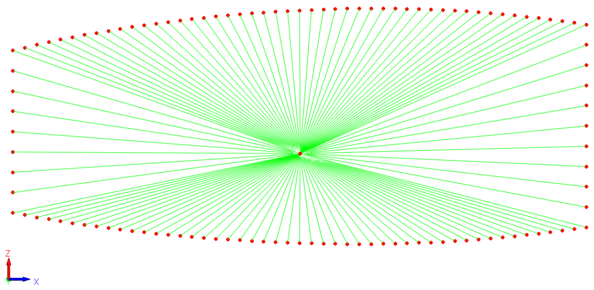


Fig. 8 : RBE2 elements from mid node to outer wing box nodes.

Table 7: RMSE for the output of AMLoad surrogate model.

Output Parameter	**ANN**	**RBF**	**Poly-glm**	**Poly2**
C_{fx}	0.02	0.04	0.03	0.03
C_{fz}	0.11	0.18	0.12	0.12
C_{my}	0.18	0.48	0.16	0.23

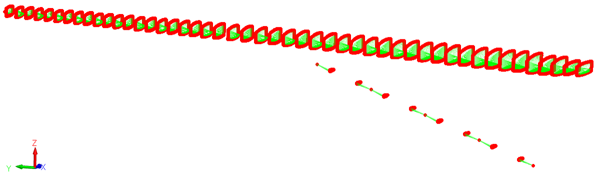


Fig. 9 : RBE2 elements applied on the full wing and strut.

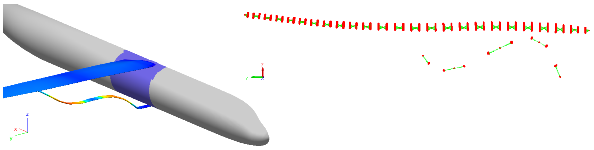


Fig. 10 : Structural bending mode splined to CFD model (left) and structural model (right).

5 MDO Results

The LoFi MDA workflow with surrogates from PROTEUS and AMLoad has been implemented in the Remote component environment (RCE) environment and is shown in Figure 11. For a single point, the workflow requires about 3 - 4 iterations to converge and takes roughly 20 minutes. To perform an optimization study, a surrogate of the entire workflow is created. For this, 60 point DOE study has been performed. To create the surrogate, Kriging model with exponential correlation function and 1st order regression polynomial is used. The input and the output parameters for the surrogate is shown in the Table 8. Using the k-fold cross-validation method, a RMSE of 87 kg is obtained which is an acceptable error for the first attempt. Figure 12 shows the sensitivity of the fuel mass with respect to the input variables of the surrogate. A detailed analysis on the trends of the DOE is discussed in the companion paper [2]

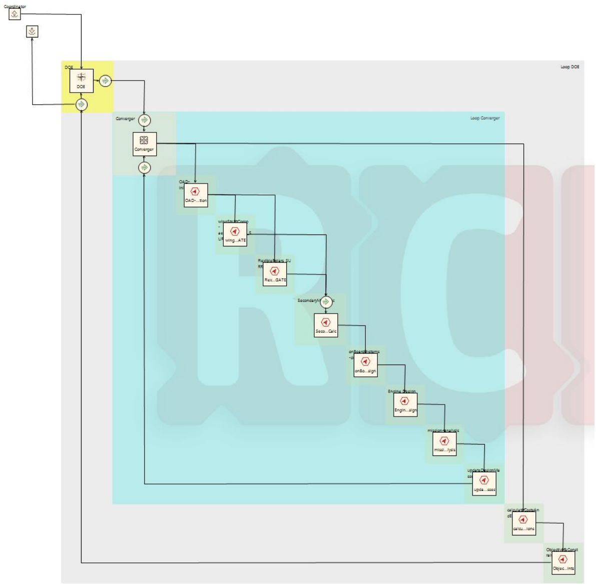
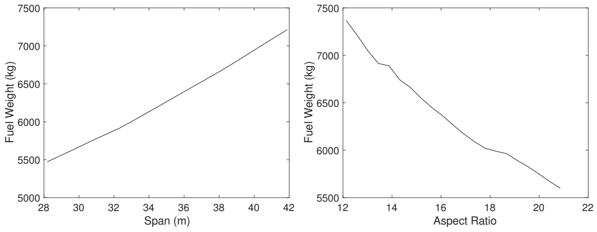


Fig. 11 : MDA workflow implemented in RCE

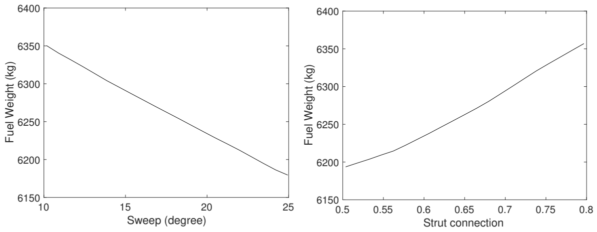
Table 8: Description of input and output variables for surrogate model of the MDA workflow.

Input Variables	**Bounds**	**Units**
AR	12-21	-
Sweep	15-25	degree
Span (b)	28-42	m
Strut t/c (st)	0.09-0.15	-
Wing t/c (wt)	0.09-0.15	-
Strut location	0.5-0.75	-
Output Variables		
Fuel Mass		

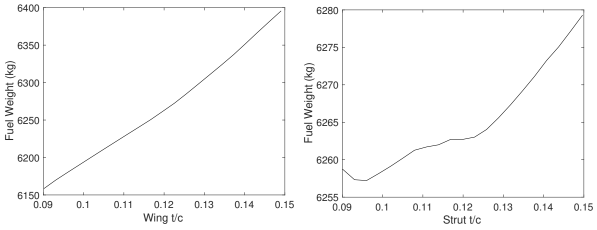
The optimization is now performed on this Kriging surrogate. The objective of the optimization is to reduce the fuel mass. The input parameter of the surrogate model will also be the design variable for the optimization study. Three constraints are imposed for the optimization. The first constraint is set on the wing volume, such that the wing has enough volume to carry the re-



(a) Span (b) AR



(c) Wing Sweep (d) Strut connection



(e) Wing t/c (f) Strut t/c

Fig. 12 : Sensitivity of the input parameters to the output parameter

quired fuel. The wing volume is calculated using Equation 1.

$$V_{wing} = \frac{b^2}{\mathrm{AR}} wt \frac{b}{\mathrm{AR}} \tag{1}$$

To make sure the local AoA of the aircraft at cruise is not too high, the second constraint constrains the cruise AoA to a maximum of 6 degree. Equation 2 is used to calculate the AoA required for the cruise condition.

$$\mathrm{AoA} = \frac{MTOW}{0.5\rho V^2 C_{l_\alpha} \frac{b^2}{AR}} \tag{2}$$

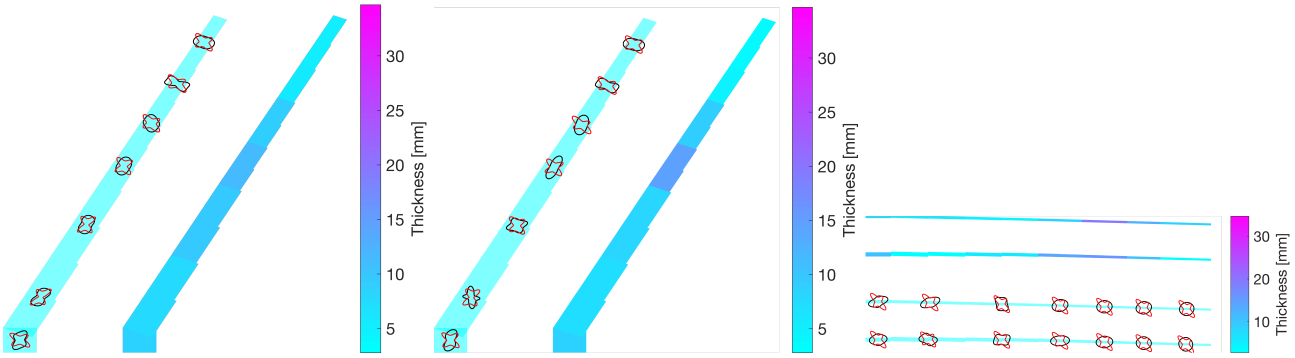
where C_{l_α} is equal to 5 and MTOW represents the maximum takeoff weight. The final constraint is on the flutter velocity being higher than the minimum equivalent flutter velocity of 144 m/s.

The parameters for the optimized design are depicted in Table 9. Ideally, the optimizer will like to go the lowest span and maximum AR for the minimum fuel weight. However, to have a required volume to carry the fuel and to be able to fly at cruise condition within 6 degree AoA, a compromise between span, AR and wing t/c is obtained. The values for the sweep and strut t/c is at its maximum and minimum respectively as that leads to minimum fuel weight as can be observed in sensitivity studies shown in Figure 12.

Table 9: Optimized Design

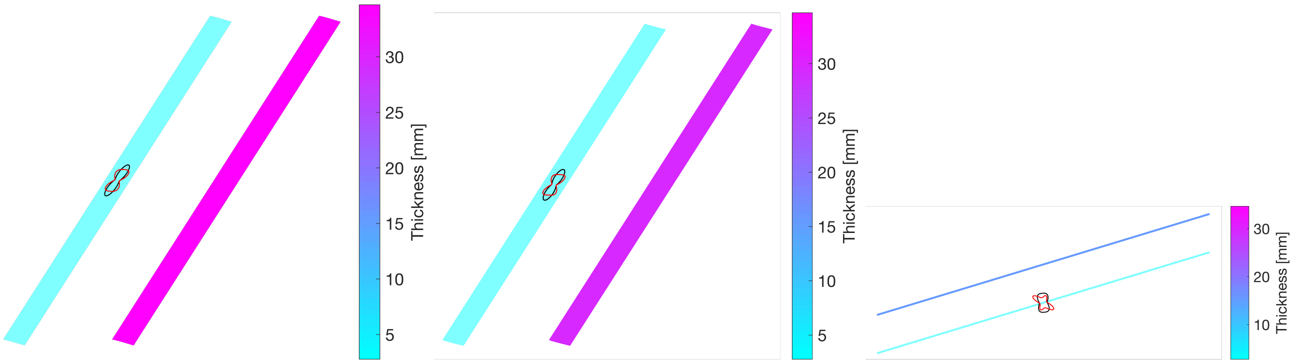
Parameter	**Baseline Value**	**Optimized Value**	**Units**
AR	15	17.7	-
Sweep	16	25	degree
Span	37	40.8	m
Strut t/c	0.1	0.09	-
Wing t/c	0.1	0.13	-
Strut location	0.5	0.5	-

For the optimized design, stiffness and thickness optimization is carried out using PROTEUS. Figure 13 and 14 depict the stiffness and the thickness information of the optimized wing and strut respectively. Figure 15 and 16 describe the value of the strain and buckling factor on the optimized wing and strut respectively. The wing is mainly dominated by strain constraints whereas the buckling is critical in only few panels. As a result the in plane stiffness in the middle part of the wing is oriented along the wing axis to maximize the load carrying capabilities whereas in the outer part of the wing, the in plane stiffness is oriented in the forward direction to introduce washout twist upon wing bending which alleviates the load. The strut is critical in both buckling as well as in strain and hence there is a pronounced effect on both the in plane stiffness and the out of plane stiffness.



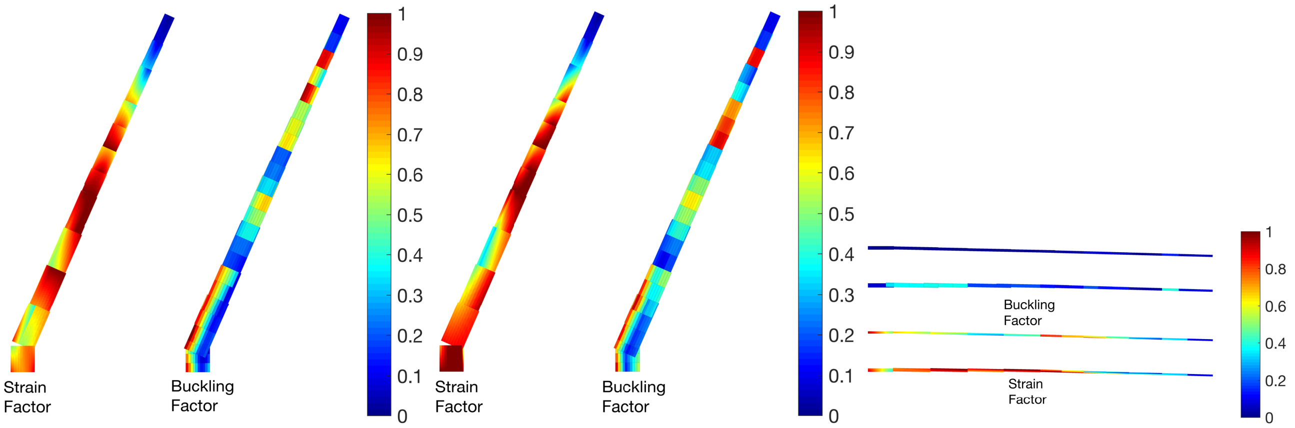
(a) Top Skin (b) Bottom Skin (c) Spars

Fig. 13 : Stiffness and thickness distribution for the optimized wing (In-plane stiffness: black, out-of-plane stiffness: red.)



(a) Top Skin (b) Bottom Skin (c) Spars

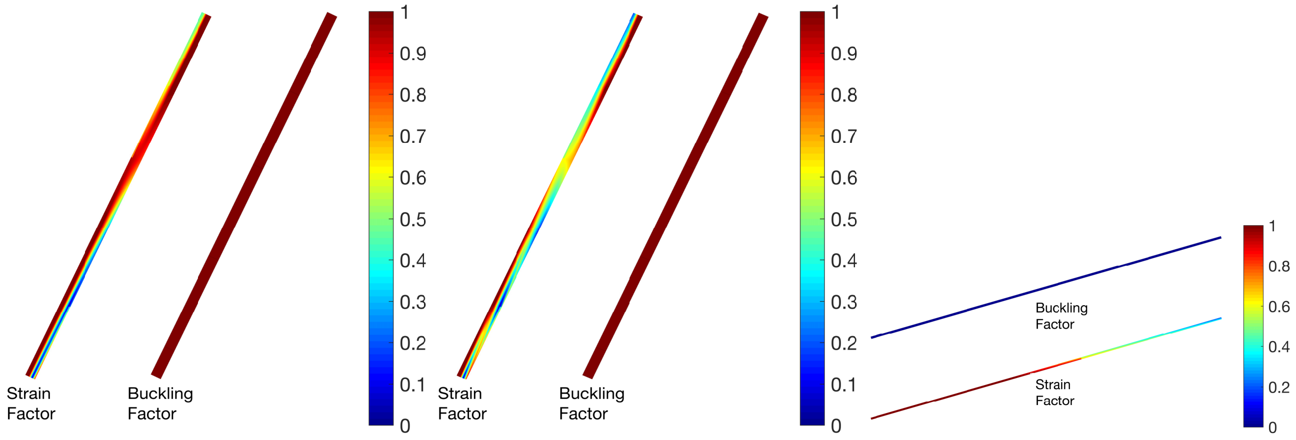
Fig. 14 : Stiffness and thickness distribution for the optimized strut (In-plane stiffness: black, out-of-plane stiffness: red.)



(a) Top Skin (b) Bottom Skin (c) Spars

Fig. 15 : Strain and buckling factor distribution on the optimized wing.

Table 10 compares the output parameters of the PROTEUS surrogate with the values obtained using the PROTEUS analysis for the optimized design. As can be seen, for wing mass the accuracy is quite good, but in the case of strut mass and flutter speed, there is still a room for im-



(a) Top Skin (b) Bottom Skin (c) Spars

Fig. 16 : Strain and buckling factor distribution on the optimized strut.

provement.

Table 10: Comparing the accuracy of the PROTEUS surrogate.

Output Parameter	PROTEUS surrogate	PROTEUS analysis	Error
Wing mass	2746.8 kg	2801.4 kg	2 %
Strut mass	757 kg	817 kg	8%
Flutter speed	213 m/s	242.8 m/s	14%

6 Conclusion

The AGILE paradigm has been used to formulate a collaborative MDA of strut braced aircraft. Aeroelastic tailoring has been integrated at the conceptual design stage through the use of surrogates. MDO of the strut braced design was performed based on the MDA formulated using the surrogates. Using PROTEUS, structural optimization of the optimum design was also performed. The output of the PROTEUS was then compared with the output from the PROTEUS surrogate. The accuracy of the surrogate still needs improvement. Different fitting methods and increased the number of sample points are the potential solutions that needs to be explored for improving the accuracy of the surrogate.

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