

LOCAL OPTIMIZATION MODEL REFINEMENT FOR THE PRELIMINARY AEROELASTIC STRUCTURAL DESIGN OF A TRANSPORT AIRCRAFT WING

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Abstract: Within this paper, the at the DLR Institute of Aeroelasticity developed software cpacs-MONA is used to evaluate the effect of the optimization model discretization on the aeroelastic assessment of a long-range transport aircraft wing using physics-based simulations at preliminary design stage. The utilized design process can be segmented into three fundamental stages: the establishment of a parametric model for the global Finite-Element-Model (GFEM), a comprehensive loads analysis of the flexible aircraft iteratively coupled with a structural optimization. As a design variable for the structural optimization, the thickness of the shell elements of a design region from the load-bearing wing structure can be adjusted to fulfill the objective function – minimize the wing-box mass under consideration of aeroelastic constraints like control surface efficiency and allowable stress or strain values, depending on the material. The design variables can be combined to design regions to reduce the size of the optimization task. For this investigation, three different fidelity levels are generated within cpacs-MONA to explore the effect of the discretization of the design variable fields on the structural mass of the wing-box together with the influence on the elastic loads, the dynamic behavior, and the resulting aeroelastic stability of the entire aircraft. Firstly, the default fidelity model – automatically generated by cpacs-MONA – is set up and is further stated as ‘Mid’ fidelity configuration. In addition to the default model, a ‘Low’ fidelity model with only the half number of design regions for the upper and lower skin is set up, followed by a ‘High’ fidelity model, where the middle region of the wing’s skin elements is discretized in very fine design fields. The resulted operating empty mass varies between one metric ton for the low-fidelity compared to the high-fidelity model, where the latter is less than one percent lighter. Regarding the stiffness, the model with higher resolution is less stiff, resulting in about three percent more tip deflection – both for translation and rotation – of the wing in $1g$ -flight condition. In terms of dynamic behavior, the first elastic eigenfrequency varies again about one percent between the high and low optimization model resolution which leads to nearly no significant influence on the aeroelastic stability of the different fidelity models. For a better understanding, two even more reduced fidelity models (‘Min’ and ‘Ultra-Low’) are set up and investigated to get the experience, when the results start to considerably differ with respect to the optimization model discretization. For the ultra-low-fidelity model, where only four design fields each are provided for the upper and the lower skin surfaces, a ten percent reduction in flight twist deformation eventuates compared to the high-fidelity model.

1 INTRODUCTION

One of the main objectives of the EU Flight Path 2050 is to significantly reduce the negative emission of future commercial aircraft designs. In addition to the thrust-specific fuel consumption and the ratio of lift to drag, the structural mass of the aircraft are key factors in reducing the aircraft's fuel burn. The structural mass can be improved by using suitable materials or by optimizing the load-bearing structures. Within the conceptual or preliminary design stage of a new aircraft development, fast but reliable simulation results have to be available to find an optimum design. In recent years, Finite Element Methods have been increasingly used in design processes as a fast tool to determine in-flight deformations, structural Eigenfrequencies or aeroelastic behavior under complex load conditions. To rapidly obtain simulation results during the early stages of a new design, simplified simulation models are typically employed. One disadvantage of simplified discretization during optimization can be, that local effects like control surface effectiveness or local loads coming from the landing gear or engine attachment can affect a large area of the optimization model and thus lead to increased stiffness and a significant mass increase. Figure 1 exemplarily visualizes a resulted thickness distribution utilizing the default discretization within cpacs-MONA and highlights the regions of potential local effects.

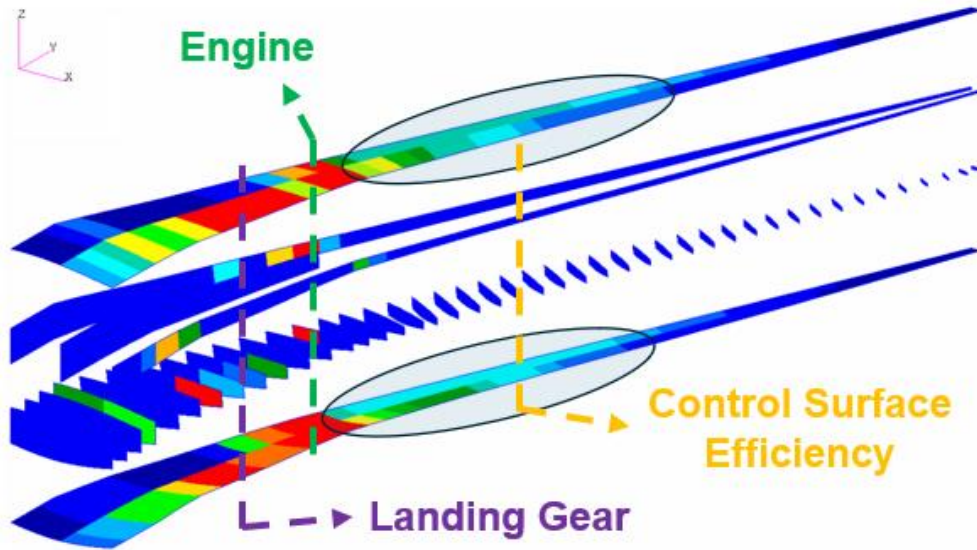


Figure 1: Local effects influencing the structural thickness of the wing design with the default (mid-fidelity) optimization model discretization.

A more detailed discretization of the entire optimization model though is highly computationally demanding, especially when a large number of load cases are considered. This is true even with the ongoing advancements in modern computer performance and the adoption of high-performance computing technologies. A local refinement at significant wing-box regions of the optimization model can be an adequate solution to improve the structural design, while keeping the speed of the simulation within reasonable limits.

In 2014, Kenway and Martins [1] utilized 54 design fields each for the upper and lower sides of the wing-box skin component (108 in total) – three in chordwise direction and 18 spanwise – for the structural thickness optimization of the Common Research Model (CRM) in combination with planform shape and airfoil shape variables in a multidisciplinary optimization (MDO) task.

For the undeflected Common Research Model (uCRM) configuration Brooks et. al. [2] engaged the structural optimization with one design field between two ribs surrounded by the front and rear spar – comparable to the low-fidelity model presented in this study – leading to 48 structural design fields each for the upper and lower skin of the main wing-box.

Bramsiepe et. al. [3] separated the upper and lower side of the wing-box composite skin of the XRF1-DLR-C configuration into 22 fields each to perform a lamination parameter optimization together with blending constraints leading to 738 structural design variables for the main wing.

None of the afore mentioned publications investigated the influence of the design field discretization on the results. Given the fact, that cpacs-MONA is an extensive aeroelastic design process with an iterative coupling of loads and structural optimization, not only the impact of the investigated discretization of the optimization model on the structural mass of the wing-box but also its influence on elastic loads, dynamic behavior, and the resulting aeroelastic stability of the entire aircraft is explored. Figure 2 exemplarily visualizes the design field discretization for the three fidelity models used for the main investigation. Their effects on the main results of cpacs-MONA are presented in the section 4.1 to 4.4 within the results chapter. In section 4.5, the results of the two even more reduced fidelity models (‘Min’ and ‘Ultra-Low’) are conclusively highlighted compared to the former investigated results.

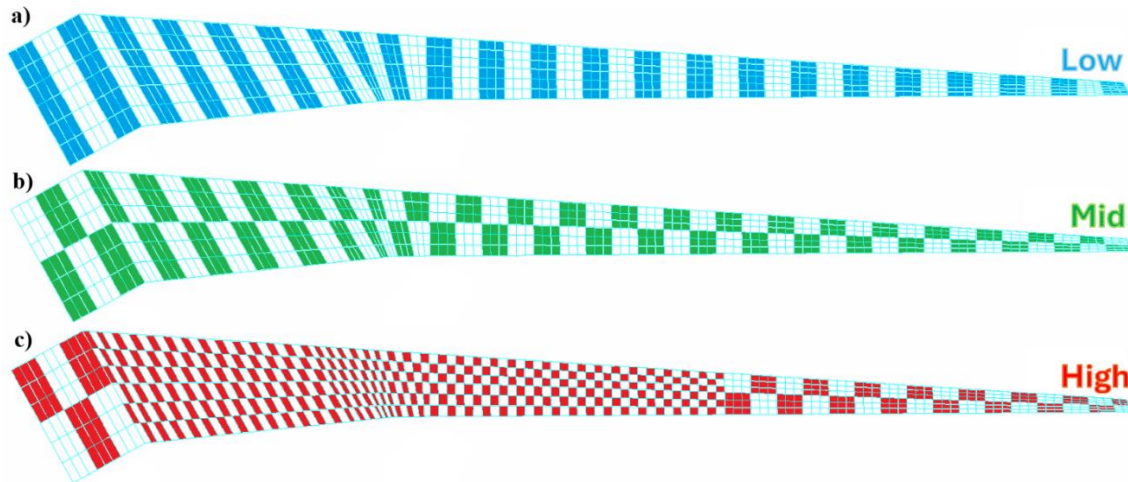


Figure 2: Design variable resolution of the skin components for the three different optimization model fidelity levels.

2 THE CPACS-MONA PROCESS

A basic aeroelastic structural design process can be defined by two steps: Firstly, the loads analysis of the flexible aircraft structure and secondly the structural design, using structural optimization methods considering aeroelastic constraints like sufficient control surface efficiency. Since the loads and structural properties are loosely coupled, such process ought to run until convergence with respect to the structural weight and the loads is achieved. In order to ensure consistency of the simulation and optimization models for the loads analysis and the structural optimization, a specific parameterization concept has been developed at the German Aerospace Center (DLR) at the Institute of Aeroelasticity (DLR-AE) over the last decades. The computer program ModGen [4] has been developed to insure the mentioned consistency of the models. It sets up all necessary

simulation and optimization models for the aeroelastic structural design process. Starting with ModGen, the basic aeroelastic structural design process at DLR-AE, named MONA is evolved. The name MONA is an acronym for the two basic computational programs involved. It is at first the already mentioned computer program ModGen for the model set-up and MSC Nastran [5] as Finite-Element-Analysis (FEA) software for the loads analysis and the structural optimization.

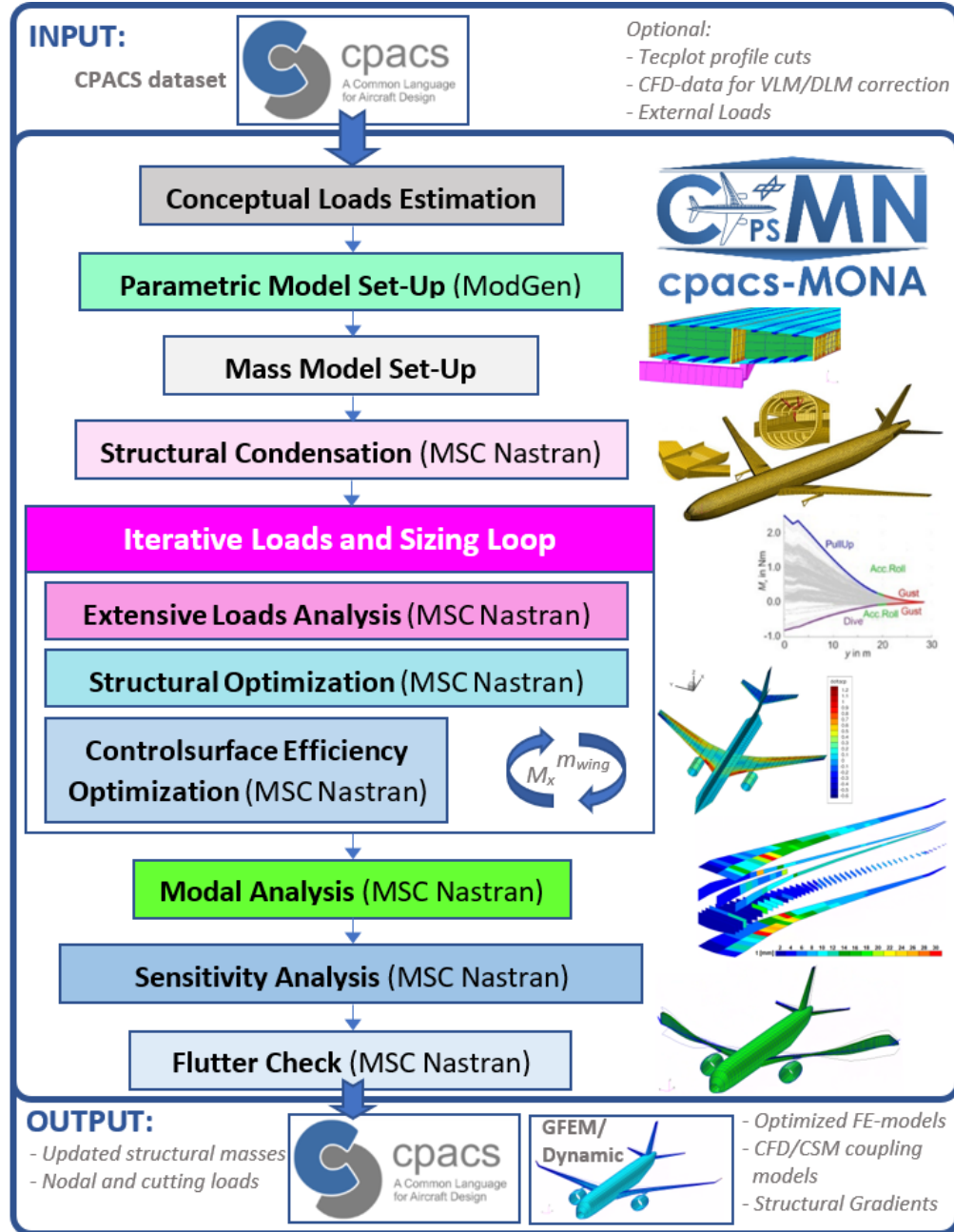


Figure 3: Process flow of the automated aeroelastic structural design process cpacs-MONA.

An automatized process called cpacs-MONA [6] has been derived from the basic MONA process at DLR-AE to perform aeroelastic structural design for various aircraft configurations at the preliminary design phase using physics-based simulations. cpacs-MONA combines many modules written in different programming languages forming an automated process as shown in Figure 3.

cpacs-MONA is integrated and applied in DLR wide established design processes ([7], [8]) or high-fidelity multi-disciplinary-optimization (MDO) chains ([9], [10], [11], [12]) using a Common Parametric Aircraft Configuration Schema (CPACS – [13]) dataset for data exchange. cpacs-MONA is written in Python code and modular. Therein, the necessary aircraft data defined in a CPACS dataset, are at first extracted. CPACS describes a wide range of aircraft characteristics like the outer geometry (profiles and segments), the global aircraft parameters (e. g. the TLARs), the topology of the inner structure, the engine outer shape, the material and much more. Besides, the aircraft information, processed information like aerodynamic data, aircraft loads, detailed mass distribution for each component, together with tool parameters can be stored in the CPACS dataset. cpacs-MONA automatically reads out the information about the wing planform, the wing inner topology and initial component thicknesses together with the engine, pylon, and landing gear positions and dimensions. It also uses information about aircraft masses like design, primary and secondary masses plus the dimensions of the control surfaces, and the borders of the fuel tanks. With this information, cpacs-MONA creates suitable input-files for the involved modules. For ModGen, each component (wing, horizontal and vertical tail, fuselage) is built separately and is executed in parallel. All components are combined to the GFEM/Dynamic. GFEM stands for global Finite-Element-Model, and dynamic expresses the applicability of the model for structural dynamic and aeroelastic analysis (e. g. flutter analysis). Furthermore, the MSC Nastran simulations like the static aeroelastic trim analysis, the dynamic gust analysis or the structural optimization analysis can each be executed in parallel within the individual steps.

The process starts with an estimation of preliminary loads based on conceptual design methods according to [14], followed by an estimation of a generic beam model representing the fuselage stiffness. The conceptual loads are used for a preliminary cross-section sizing (PCS) within ModGen [15]. Due to the PCS, a more realistic wing representative with respect to the shell thickness distribution and bar properties is provided. As shown in Figure 4, the wing ribs, spars, and skins are modeled with shell elements. The other wing component structures like the spar caps, the inner reinforcement structure, or the stringers are modeled with bar or beam elements. A parametric elastic pylon model is also available to account for the elastic interaction of the engine with the wing and vice versa.

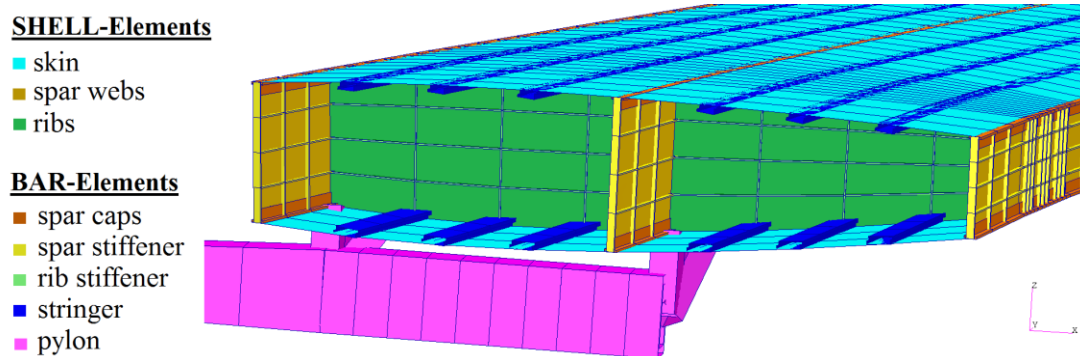


Figure 4: Wing topology of the FE-models highlighting the utilized structural elements.

For a conclusively substantiated aeroelastic analysis, reasonable mass models have to be established. A mass model module reads out the mass-breakdown for each component and creates a model with distributed mass and inertia entities in line with the given geometrical space of the

individual component. The fuel tank's volume is calculated according to the geometrical borders (such as ribs and spars) as defined in CPACS. The masses of the engine and landing gear are extracted from the dataset and converted into Nastran *CONM2* elements. The resulting operating empty mass (OEM) together with defined combinations of fuel and payload/passenger masses form the design masses and different mass cases, important for the loads analysis of the aircraft.

To reduce the size of the GFEM/Dynamic for the extensive loads analysis, the stiffness of the structural model is condensed to the loads reference axis (*LRA*) points. Such condensed model is set up by using RBE3 elements with UM option, which are generated by ModGen, forming the so-called Guyan-reduction [16]. This model has the same dynamic characteristic (mass and stiffness) as the full GFEM/Dynamic but much less degrees of freedom.

For this paper, hundreds of static load cases are simulated. They are based on the regulations CS25.335 [17] containing symmetrical pull-up and push-down maneuvers, yawing and rolling maneuvers together with *1g*-level flight loads paired with dynamic gust encounters are simulated. For each wing fidelity model six different mass cases of the aircraft are considered. For the steady maneuvers, MSC Nastran Solution 144 is used and Solution 146 for the dynamic gust simulations [18]. In context of the *2.5g* pull-up maneuvers, the inner ailerons are symmetrically deflected to alleviate the maximum loads according to [19]. The load cases with the maximum and minimum cutting moments for bending and torsion as well as forces for shear are selected for each wing-like component. The forces and moments acting on the primary structure of these load cases are extracted and used for the structural optimization of the wing-like components.

MSC Nastran Solution 200 [20] is used for the structural optimization. The optimization model consists of the definition of design variables, constraints, and an objective function. The objective function for the structural optimization is the wing-box mass to be minimized under consideration of aeroelastic constraints like control surface efficiency, allowable strain values for composite materials or stress limits for metallic materials per design field. As design variable, the thicknesses of the shell elements for the load-carrying wing structures can be adjusted to fulfill the constraints. The design variables are combined to design regions to reduce the complexity of the optimization.

The loads analysis and structural optimization are conducted iteratively, while the mass and the stiffness of the simulation models are updated after each step until the mass and the loads of the aircraft configuration converge. This degree of process automatization emphasizes that cpacs-MONA does not only generates different simulation models for different optimization model fidelity levels to evaluate the individual influence on the loads or on the structural mass. To a greater degree, it optimizes the load-carrying wing structure of each aircraft configuration in an iterative loads and structural optimization loop to best bear the loads emerging on the different fidelity levels. At the end of the convergence loop, additional analysis like a subsonic flutter check or structural sensitivity analysis can be performed within cpacs-MONA according to the purpose of the output of the design task.

3 THE AIRCRAFT CONFIGURATION

As configuration for this investigation, the within the DLR Project LamTA (Laminar Tailored Aircraft) long-range aircraft configuration, which is currently under development [21], is used. The main objective of the project is to integrate laminar flow technologies (natural and hybrid)

into the wing, tail, nacelle, and fuselage of a 2035 long-haul aircraft. Intermediate results indicate a potential reduction of 16 percent in block fuel. An additional increase of the wing aspect ratio leads to fuel savings of up to 24 percent. These findings, which are fundamental to DLR's LamTA project, will be refined in future work through detailed disciplinary analyses.

3.1 Top-Level Aircraft Requirements

The Top-Level Aircraft Requirements (TLARs) derived from the overall aircraft design (OAD) for the DLR LamTA configuration are partially highlighted in Table 1. The aircraft is a derivative from the oLAF configuration [22], a development of a former DLR project.

Table 1: Top Level Aircraft Requirements for the LamTA configuration.

Aircraft Parameter	Value
Operating Empty Mass	113 t
Max. Take-off Mass	210 t
Max. Payload	54 t
Design Cruise Mach	0.83
Design Range	6000 NM
Max. Cruise Altitude	FL 430
Entry Into Service	2035

3.2 Geometry

The outer geometry of the LamTA configuration is shown in Figure 5 in a three-side-view. It is equipped with two ultra-high bypass-ratio turbofan engines with a bypass-ratio of 12:1, mounted under the wing. Each engine has an outer diameter of 4 m and an operating-mass of around 8000 kg. The span is designed to fit into the category E of the ICAO Aerodrome Reference Code.

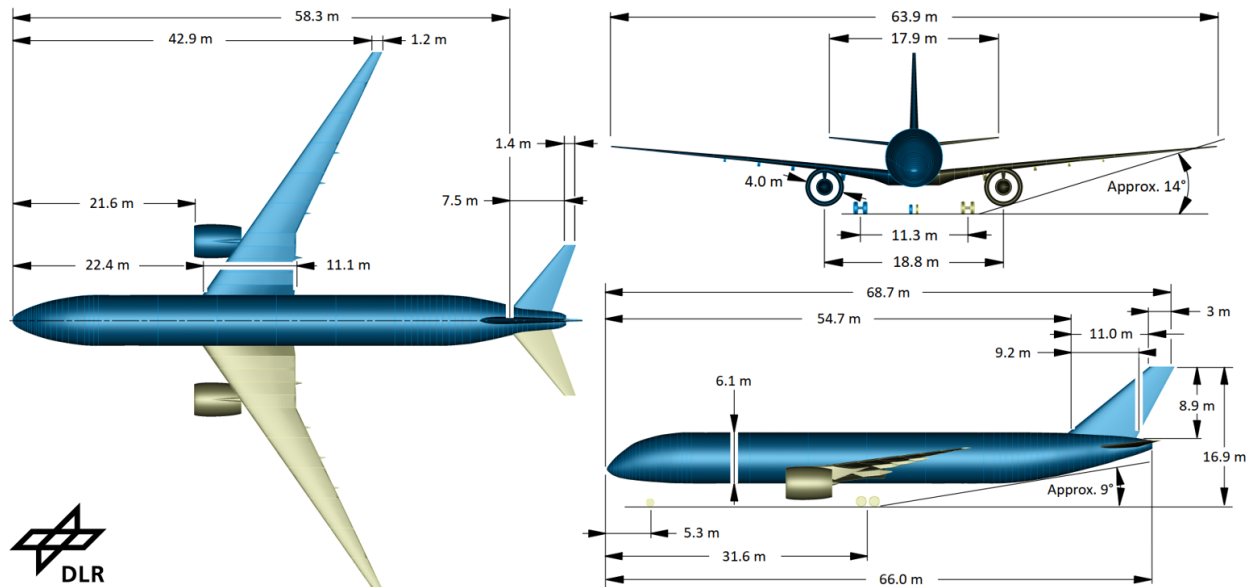


Figure 5: Three-side-view of the LamTA configuration.

The key planform characteristics of the LamTA main wing are presented in Table 2. The main parameters describing the aerodynamic characteristics – namely the relative profile thickness and the JIG-twist distribution – of the main wing are shown in Figure 6 over the half-span.

Table 2: Key planform parameters for the main wing of the LamTA configuration.

Parameter	Main Wing
Area	346 m ²
Span	63,9 m
Aspect Ratio	11.75
Taper Ratio	0.106
MAC	7.15 m

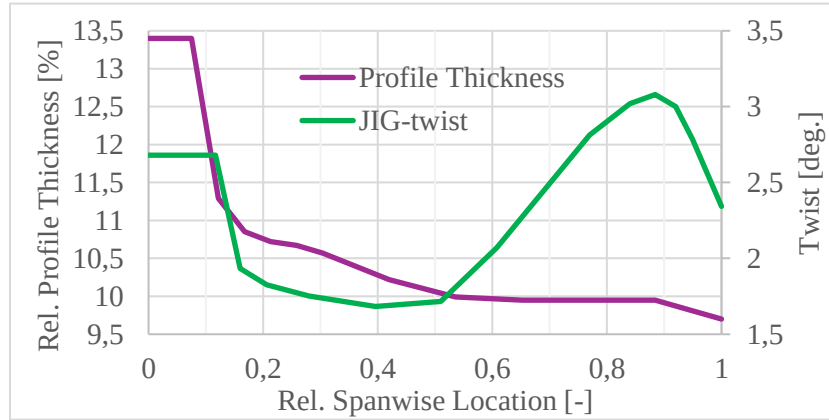


Figure 6: Profile thickness and JIG-twist distribution over the half-span of the main wing.

3.3 Simulation Models

To perform a conclusively substantiated aeroelastic assessment, suitable simulation models for the FEA-software have to be set up. Structural FE-models represent the stiffness of the airframe and aerodynamic panel models depict the aerodynamic forces. Reasonable mass models for various mass configurations induce the inertia loads.

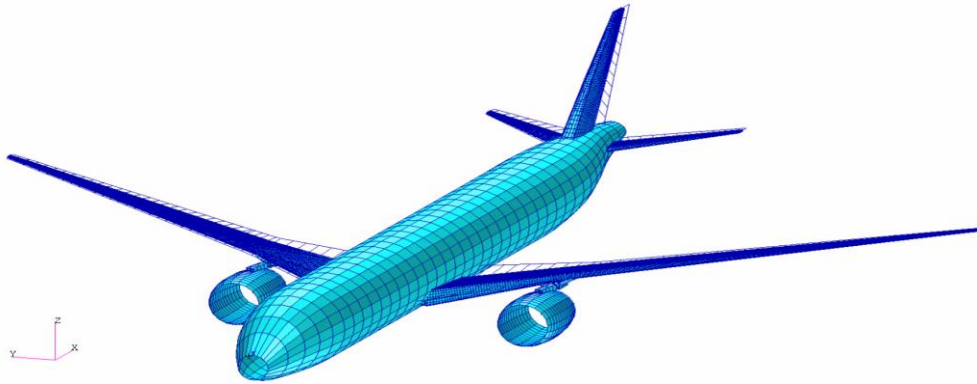


Figure 7: Global Finite Element Modell (GFEM/Dynamic) of the LamTA configuration.

3.3.1 Structural Model

cpacs-MONA generates the structural models of an aircraft configuration using the model generator ModGen. The full model of the LamTA configuration consists of approximately 9.200 FE-nodes and 21.000 FE-elements and form the GFEM/Dynamic as highlighted within Figure 7. The shell elements of the fuselage and engine nacelle are only for illustrational purpose. To reduce the computational effort for the extensive load analysis of the flexible aircraft, the GFEM is condensed. The condensed model consequently consists solely of 470 FE-nodes. The nodes on the load reference axis and the nodes on the leading and trailing edge, rigidly connected to the LRA with RBE2 elements, enable a surface splining between the aerodynamic and structural model. Spline elements transfer the forces and motions between the two models. The aerodynamic model is presented in subsection 3.3.3 on site 10.

The wing is equipped with a mid-spar up to the kink to be able to withstand the local loads acting at the engine and landing gear attachment. 46 ribs are located between the front and rear spar of the LamTA wing. An illustration of the rib distribution and the spars together with the skin elements is shown in Figure 8. The figure also highlights the element discretization of the load-carrying structural model. For this investigation, the wing material was exchanged from composite to metal to simplify the optimization task. Aluminum 7075 alloy is used for the upper wing skin, and aluminum 2024 (better suited for cyclic loads) for the lower side to generate the stiffness and mass properties for the wing. Structural models of the control surfaces do not exist.

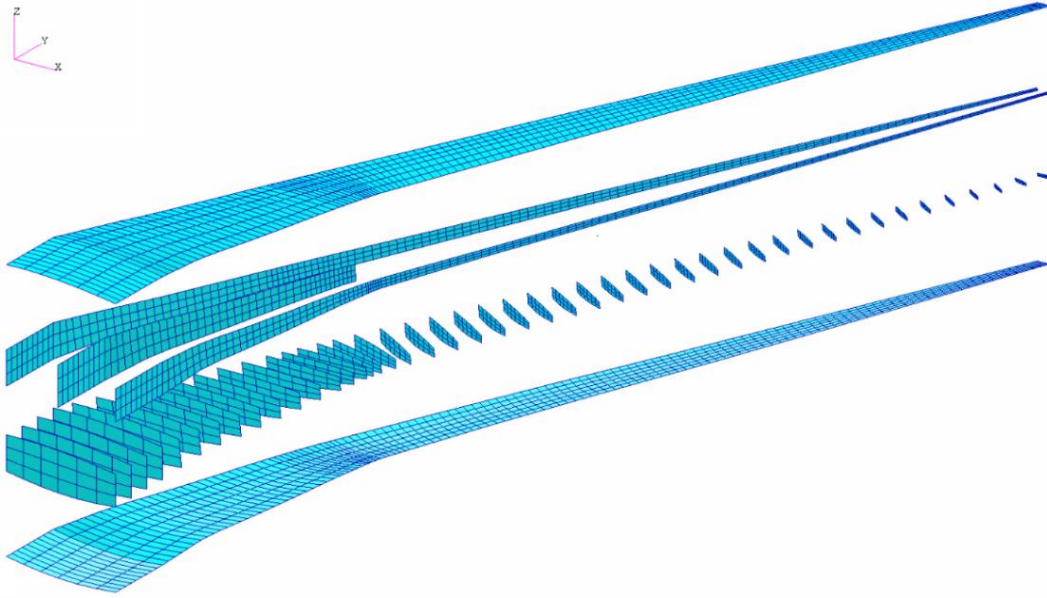


Figure 8: Exploded view of the main wing FEM components and their element discretization.

3.3.2 Mass Model

To describe the basic characteristics of the mass cases, an internal ID is used. This ID is complemented with the percentage indication of the payload and fuel compositions with the center of gravity (see Table 3).

Table 3: Investigated mass cases listing the corresponding fuel and payload conditions.

	MOOee	MFOeF	MZOAe	MTOAa	MTOfF	MCRUI
Design Mass	OME	‘delivery’	MZFM	MTOM	MTOM	‘cruise’
Mass [t]	120	207	174	210	210	182
Payload [%]	0	0	100	100	6	75
Payload [t]	0	0	54	54	3	41
Fuel [%]	0	100	0	41	100	25
Fuel [t]	0	87	0	36	87	22
xCG [m]	29.8	30.8	29.4	29.4	30.8	30.5
xCG [%MAC]	20	35	15	15	35	30

3.3.3 Aerodynamic Model

The automatically generated aerodynamic model is shown in Figure 9. This model consists of macro panel elements for the vortex and doublet lattice method (VLM [23] and DLM [24]). Within the elastic trim analysis, the macro panels of the wing-like structures are modified for numerical reasons to account for the geometrical effects like camber and twist of the wing. Aerodynamic corrections to account for compressibility effects have not been considered within this publication. The control surfaces like elevator, rudder, and ailerons are also defined within the aerodynamic model according to their definition within the CPACS dataset.

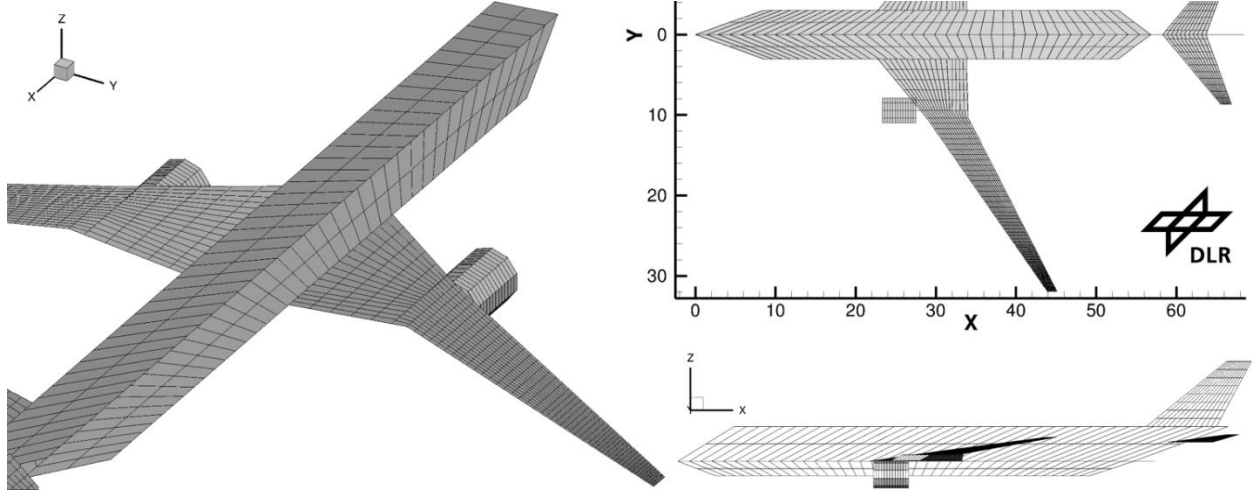


Figure 9: Aerodynamic panel model of the LamTA configuration.

3.3.4 Load Case Setup

For the load case setup, a flight envelope is defined according to the requirements of CS25.335 [17] for the given design speeds VC (MC) and diving speed VD (MD), where VC is set to V_{MO} (maximum operating speed) as specified within the CPACS dataset at sea-level, where the EAS equals the true airspeed (TAS). The $1g$ -stall speed V_S and the design maneuvering speed V_A are calculated based on the specified values of $C_{L,max}(M)$, $C_{L,min}(M)$ and $C_{L\alpha}(M)$ as presented by Lomax [25]. V_a and V_h are stall speeds at varied load factors (n_z) and V_B is the design gust speed. Figure 10 visualizes the various design speeds forming the flight envelope in true airspeed for the mass case $MCRUI$ of the LamTA configuration. Within the figure, the information for constant Mach numbers (Ma) and constant calibrated airspeed (CAS) is also given.

The considered load cases for the LamTA configuration include quasi-static symmetrical together with asymmetrical maneuvering loads, dynamic gust loads using $1-\cosine$ gust encounters with different gust-gradients ($9m \leq H \leq 107m$), and conceptual ground loads. A maneuver or gust load case is completely defined by the specification of a particular flight point (speed and altitude), a vertical load factor (n_z) and a specific mass configuration. For the trim conditions of the maneuver load calculation, symmetrical pull-up at $2.5g$ and push down (up to $-1g$) as well as various yaw and roll maneuvers are taken into account. For the main design driving load case – the $2.5g$ pull-up maneuver – a passive maneuver load alleviation (MLA) is considered during the load simulation. Therefore, the inner aileron is extracted by a pre-defined angle of 20 degrees to diminish the local lift at the tip of the wing and shift the resulting lift forces more inboard for a reduction of the maximum wing bending moment.

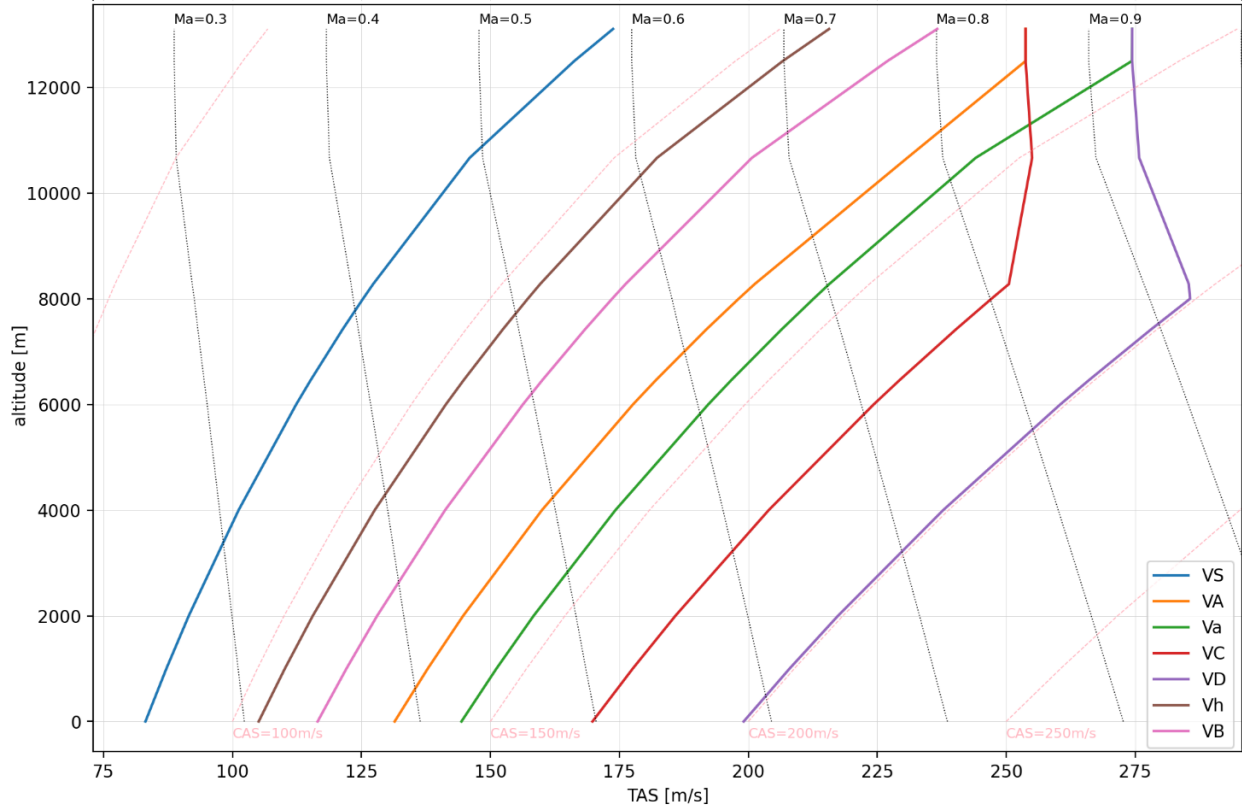


Figure 10: TAS flight envelope for the load case definition.

To select the load cases for the structural optimization, so-called load envelopes are generated for a set of monitoring stations. The basis of the envelopes are pairs of cutting loads which are built for each load case and combined into a diagram. The envelope is the resulting convex-hull formed around all load cases. Within cpacs-MONA, cutting moments for torque (M_y), bending (M_x), and shear forces (F_z) are considered for each wing-like component.

3.3.5 Structural Optimization Model

The objective function for the structural optimization is the wing-box mass to be minimized under consideration of aeroelastic constraints like control surface efficiency or allowable stress values per shell element. As a design variable, the thicknesses of the shell elements from the load-carrying wing structure can be adjusted to fulfill the constraints. The design variables are combined to design regions to reduce the size of the optimization task. The default design regions within cpacs-MONA – forming the so-called mid-fidelity model for this investigation – are the partial skin surfaces surrounded by spars and ribs, and the partial rib and spar surfaces due to their intersections among each other. Since the wing-box of the LamTA main wing consists of 46 ribs and three spars, the optimization model consequently has 92 design regions for the ribs, 180 for the skin, and altogether 106 for the spars. In total, 378 design variables are optimized to minimize the wing-box mass of the main wing per optimization step. Table 4 lists the number of design fields for the three investigated discretization models. They only differ for the skin components, since the regions for the ribs and spars are constant for all fidelity-models. The dimensions of the reinforcement bar elements are not part of the optimization task and the overall FEM discretization is unchanged between the variants. Their dimensions are estimated within the PCS based on cutting loads.

Table 4: Number of design fields of the main wing for the three investigated fidelity models.

Model	Ribs	Spars	Skin (up)	Skin (low)	Overall
Low	92	106	45	45	288
Mid	92	106	90	90	378
High	92	106	506	506	1210

The structural optimization within cpacs-MONA is conducted in two steps. The first step uses the simulated loads to optimize the structure to withstand the loads at each flight point. For the second step, the resulting structural thicknesses from the first step are defined to be the lower bounds of the design variables. Within the second optimization step, only the aileron efficiency is the constraint to ensure sufficient roll-control for each configuration.

4 RESULTS

The following paragraph highlights the effect of the different fidelity levels of the optimization model on the main aircraft results as output of cpacs-MONA.

4.1 Effect on the Loads

The loads acting on the main wing are caused by aerodynamic lifting forces and the inertial counterparts acting on the load-carrying structure. Figure 11 highlights the wing bending cutting moment (M_x) over the relative half-span coordinate 'eta' for the mid-fidelity model.

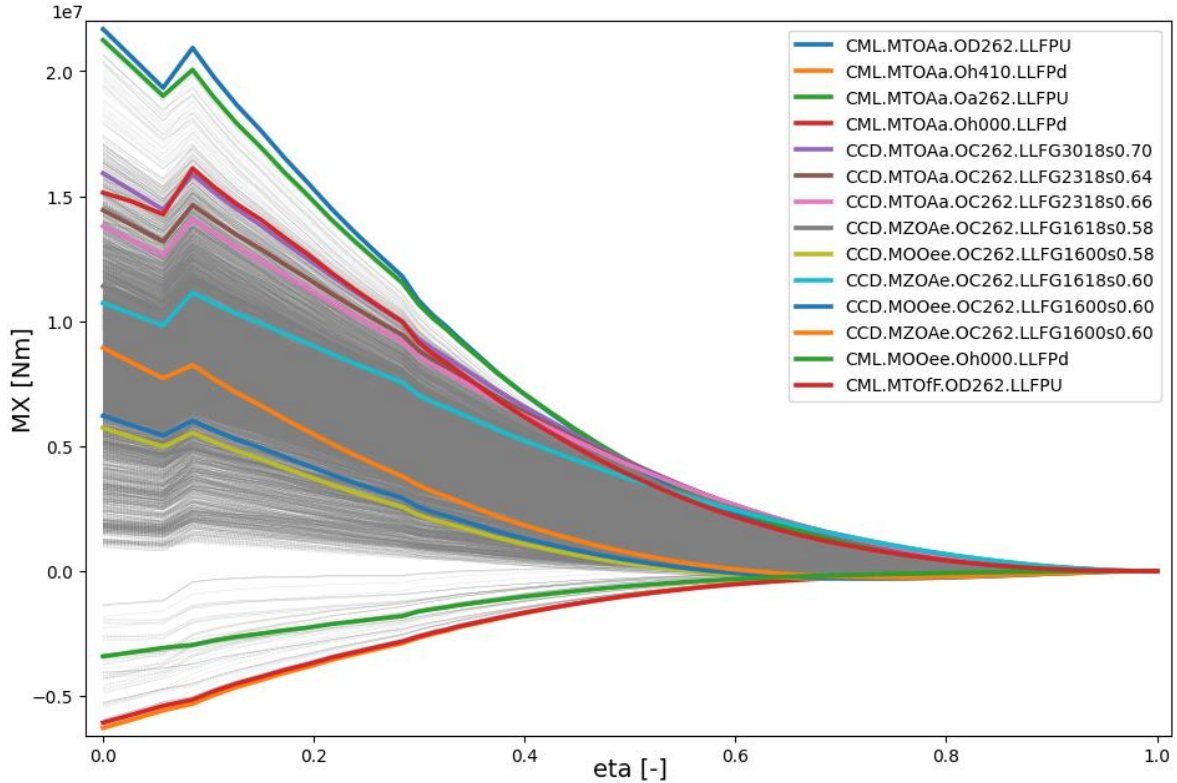


Figure 11: Main wing bending cutting moment (M_x) over the relative half-span coordinate for the default optimization model (mid-fidelity).

To reduce the computational effort of the optimization task, a component-wise load case selection is performed. Like mentioned in subsection 3.3.4, a convex-hull is computed around pairs of cutting loads for the shear forces, the bending and torsional moments, forming the load envelopes for a selected number of monitoring stations. The forces and moments of these load cases are extracted and afterwards used for the structural optimization of the wing-like components.

Within Figure 12, the two-dimensional wing cutting load envelope is visualized for the bending moment (M_x) and the torsional moment (M_y) for two exemplary wing load monitoring stations. The monitoring point *W640005* is located near the wing root (rib number 5) and *W640029* is located at rib number 29 between the engine attachment and the inner aileron. Since the load cases forming the convex hull (most outer points) are indicated with their internal load case IDs, it becomes apparent, that the maximum torsional moments are caused by the mass case *MZO Ae* with a pull-up (*LLFPU*) maneuver and the minimum torsional moments (most negative) are caused by a push-down (*LLFPd*) maneuver at *MTOAa* mass condition. The gust cases are less dominant at the location of the monitoring point near the wing root, but become more relevant at the outer section of the wing, since the maximum bending moment at *W640029* is caused by a gust (*LLFG*).

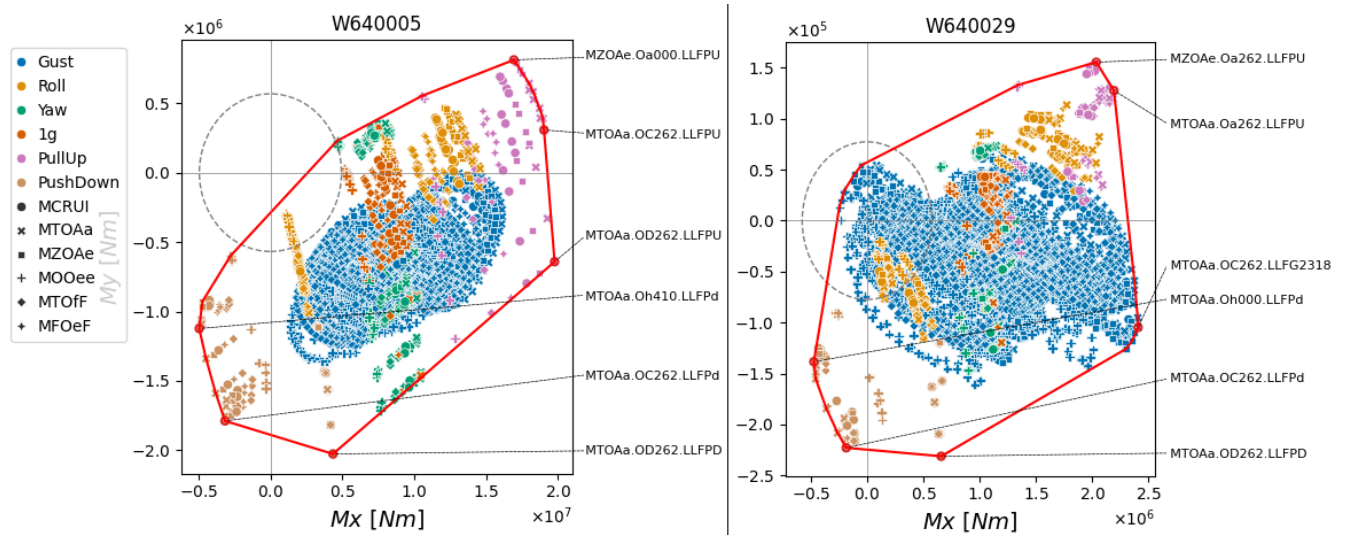


Figure 12: Cutting load envelope for the bending (M_x) and torsional moment (M_y) for the main wing load stations *W640005* and *W640029* for the default optimization model (mid-fidelity).

The effect of the different investigated optimization fidelity levels on the dimensioning loads is negatable, since the maximum bending cutting moment between the low-fidelity model and the high-fidelity model only differs about one percent and the minimum bending moment only about 0.1 percent. Regarding the torsional cutting moments, the maximum varies about 0.8 percent between the low- and the high-fidelity model.

4.2 Effect on the Structural Properties

To withstand the loads acting on the primary wing structure, the thickness of the design variables for the upper and lower skin covers, the ribs and the spar webs are adjusted by the optimization algorithm. The resulting thickness distribution for the three investigated fidelity models is shown within Figure 13. The color resolution for the upper and lower skin fields visualizes the discretization of the different fidelity models. The low-fidelity model (a) includes one chordwise design field between two ribs, while the mid-fidelity model consists of two chordwise fields.

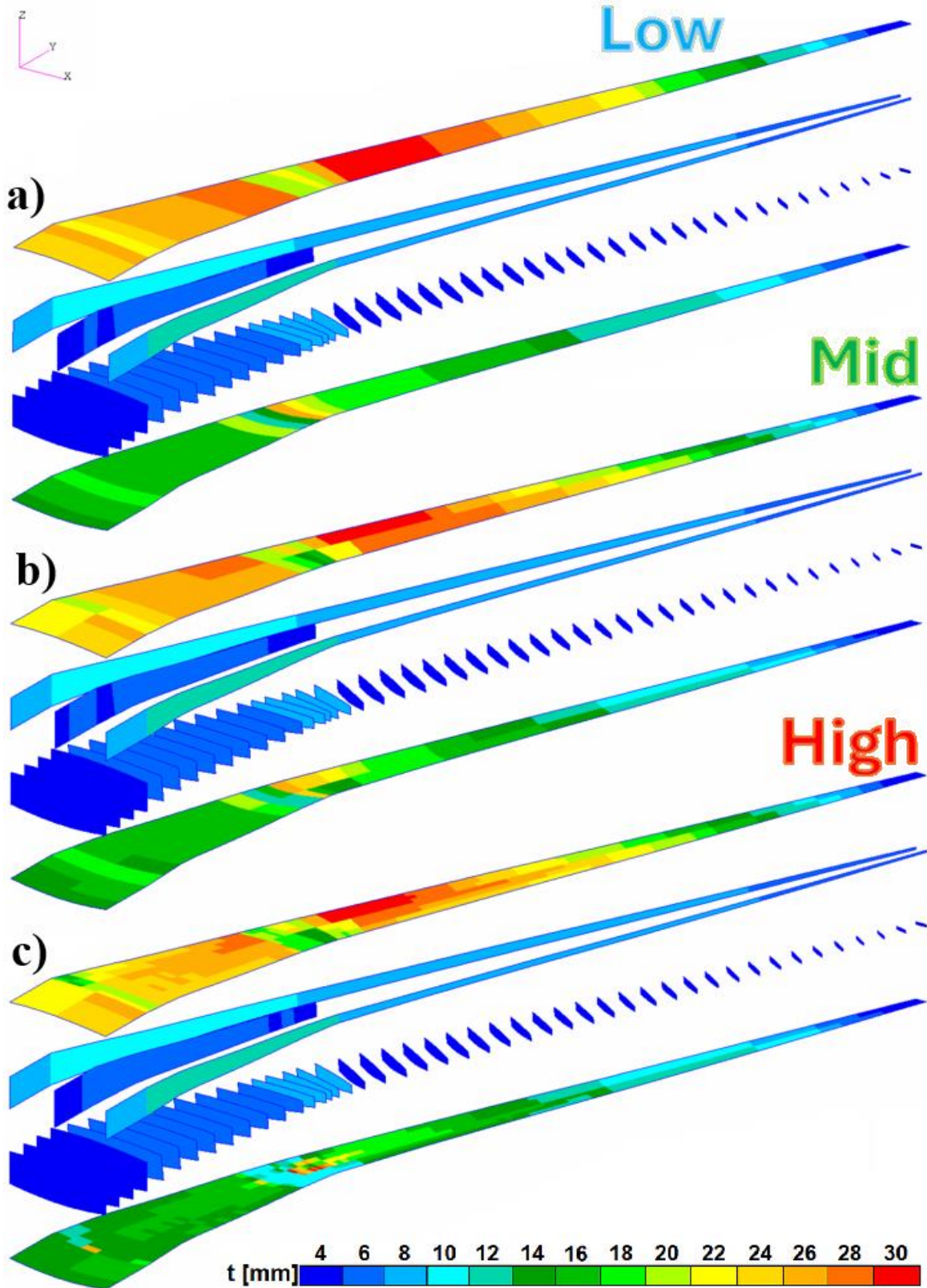


Figure 13: Resulting structural component thickness distribution of the main wing for the three different optimization model fidelity levels – exploded view.

Comparing (a) and (c) within Figure 13, it is noticeable that the region of maximum thickness for the upper skin near the kink of the wing could be reduced significantly for the high-fidelity model. The lower side near the kink also exhibits less thickness compared to the two lower-fidelity models. The rib and spar thickness does nearly not change between the different fidelity models.

The wing primary mass is the resulting mass of the FEM-optimization (sized mass) factorized with a so-called mass penalty to account for non-ideal weight penalties for the wing according to [26]. This mass penalty is due to the fact, that the sized mass of the FE-Model does not reflect the real mass of the primary wing structure. Figure 14 breaks down the mass of the available structural components for the three fidelity models of the main wing. It is obvious, that only the mass of the skin elements changes, since the other parts fidelity does not vary between the different models.

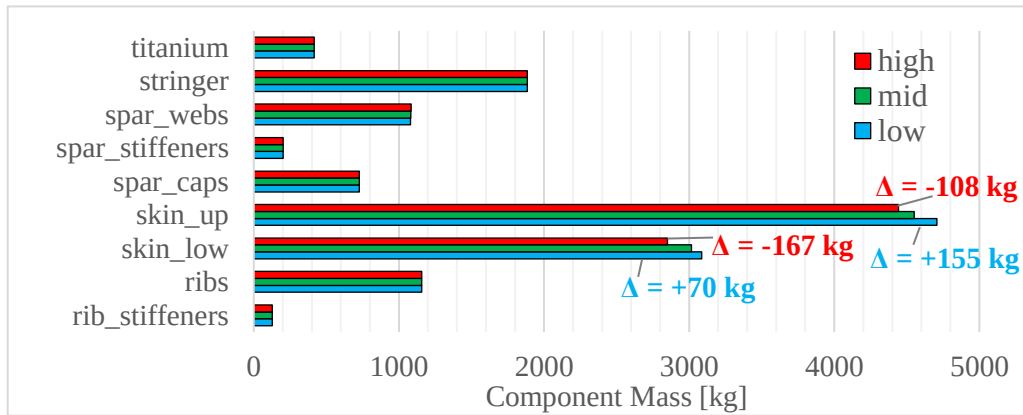


Figure 14: Main wing load-carrying structural component mass breakdown (sized FEM mass) for the three different optimization models.

Beside the requirement to withstand the resulting loads acting on the load-bearing structure, another main task of the structural Finite-Element-Model within the design phase of a new aircraft configuration is to fit the aerodynamically designed flight-twist under $1g$ -load condition. The structural component's thickness distribution on the one hand influences the mass of the structure and on the other hand the stiffness. To get an insight on how the optimization discretization influences the wing stiffness, the twist deformations over the wing span within the steady $1g$ -level flight of the different fidelity models is displayed in Figure 15. The twist at the tip varies about three percent between the low- and high-fidelity model. The investigated fidelity seems to have a small impact on the in-flight displacements, since beside the twist, the maximum vertical tip displacement only varies about two percent. So, the resulting flight shape is very similar between the investigated models.

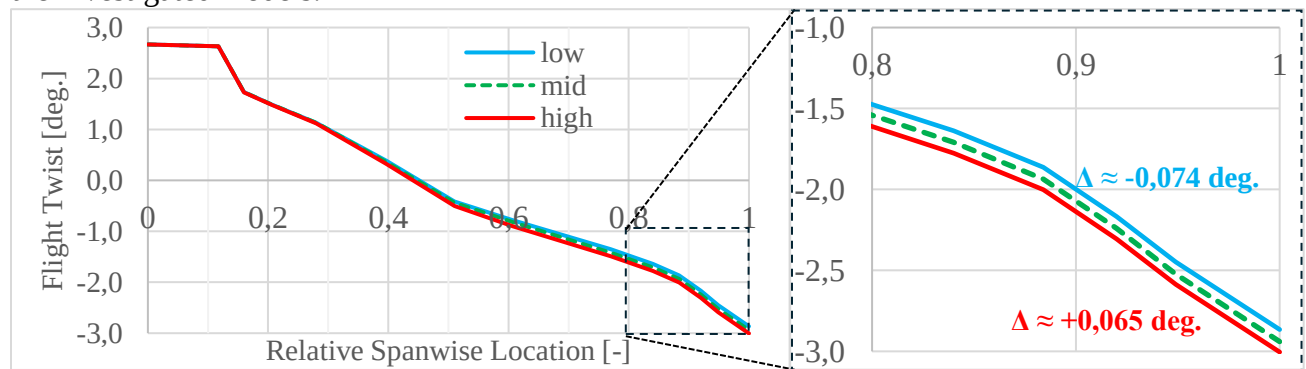


Figure 15: Flight twist distribution along the span for the three different optimization models.

4.3 Effect on the Structural Dynamics

The wing stiffness and mass distribution do not only have an impact on the deformation of the wing during flight, they also influence the structural dynamic behavior. Within Figure 16, the relative deviation of the elastic Eigenfrequencies up to mode number 50 are listed for the low and high-fidelity models in comparison to the default (mid) fidelity model. The wing of the high-fidelity model seems to be softer as the mid-fidelity model, since it's Eigenfrequencies are mostly lower. For the low fidelity model, it is the other way around. Nevertheless, the influence of the three investigated fidelity levels – again – seems to be negligible with respect to the structural Eigenfrequencies of the global aircraft since the variation lies within a one percentage band.

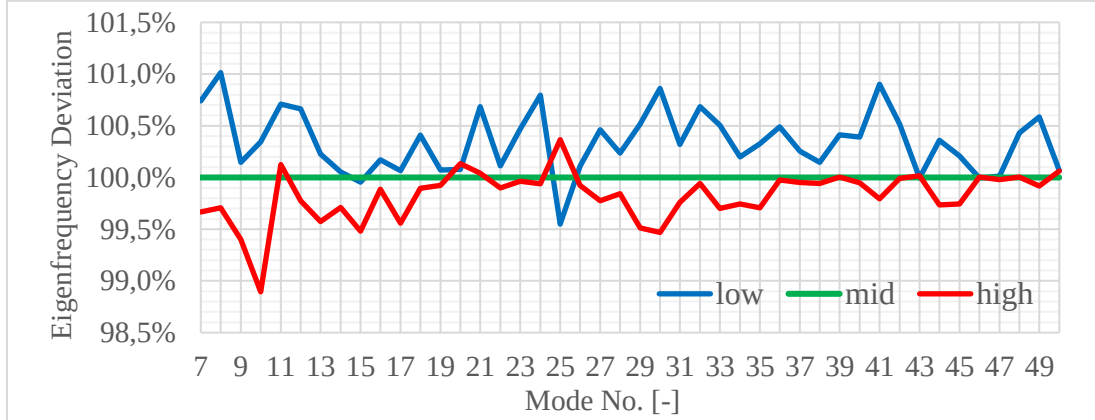


Figure 16: Relative deviation of the elastic Eigenfrequencies for the operating empty mass case of the low- and high-fidelity compared to the mid-fidelity model.

Table 5 list the Eigenfrequencies of the first symmetric wing out-of-plane bending Mode (7) and the first symmetric wing torsional Mode (30) for the three investigated optimization models, since they are relevant for an aeroelastic assessment. The first wing bending Eigenfrequency of the empty wing is with below one Hertz quite low for an aircraft configuration, but with a factor of 10, the wing bending has a sufficient frequency-distance to the first torsional Eigenfrequency.

Table 5: Eigenfrequencies of the most relevant elastic wing Eigenmodes of the three different fidelity models for the operating empty mass case.

Model	1 st sym. wing out-of-plane bending	1 st sym. wing torsion
Low	0.987 Hz	10.55 Hz
Mid	0.980 Hz	10.46 Hz
High	0.977 Hz	10.41 Hz

4.4 Effect on the Aeroelastic Stability

The subsonic flutter check at the end of a cpacs-MONA run reveals, that the LamTA aircraft is a flutter free configuration within the aeroelastic stability envelope. There is no case, where the damping of a Mode becomes negative at the performed non-matched p - k -flutter analysis using a fixed Mach at fixed density utilizing MSC Nastran's Solution 145 [18] for all six mass cases of the design up to 1.15 times the design dive speed (V_D). The Mach number is set to 0.6 and the density according to the international standard atmosphere to 0.525 kg/m^3 for the flight altitude of

8000 m. To be able to investigate the effect of the optimization discretization on the aeroelastic stability of the aircraft – although it is not realistic – the flight speed (TAS) for the LamTA configuration was increased up to 600 m/s within the flutter analysis to find a flutter case. Figure 17 illustrates the resulting damping curves of the analysis for the mid-fidelity model and also highlights the Mode shapes of the three vacuum modes revealing a positive damping crossing.

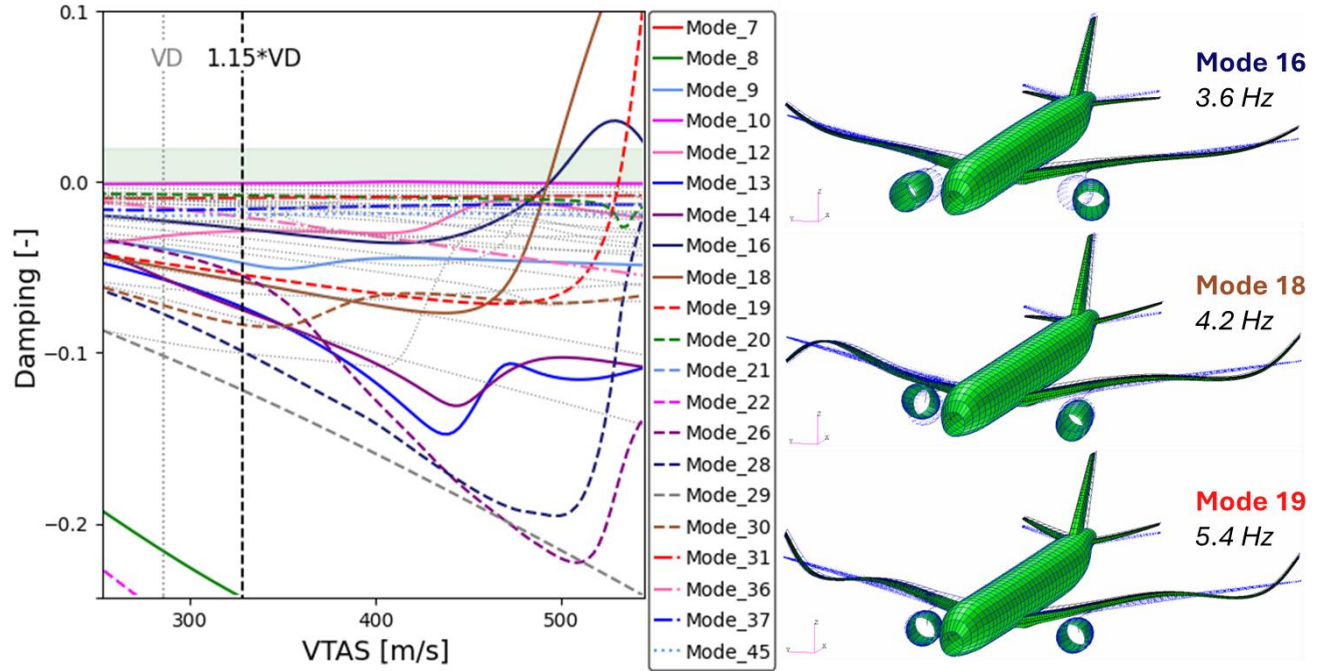


Figure 17: Flutter damping plot of the reference configuration for the MCRUI mass case with the three structural vacuum modes relevant for flutter.

Within Table 6, the flutter speeds of the three modes illustrated in Figure 17 for the three investigated models are listed. Since the Modes 16, 18 and 19 do not vary much in their Eigenfrequencies, the Mode shapes can be seen as identical for the different optimization fidelity models. The revealed trend of the flutter speeds shows, that the increased stiffness of the low-fidelity model leads to a higher flutter speed, while the high-fidelity model has the lowest flutter speed for all three shown modes.

Table 6: Flutter speeds of the three modes highlighted in Figure 17 for the three fidelity models.

Model	Mode 16	Mode 18	Mode 19
Low	496 m/s	493 m/s	533 m/s
Mid	490 m/s	487 m/s	523 m/s
High	481 m/s	484 m/s	520 m/s

4.5 Further design field reduction

Since the highlighted results for the three investigated optimization fidelity models mostly vary between one percent and therefore are quite comparable, two even more reduced fidelity models have been set up to get an idea, at what grade of fidelity the results start to differ more significantly. For the new so-called min-fidelity model, the number of design fields has been reduced by half

compared to the low-fidelity model. The new lowest fidelity model is named ultra-low and only consists of four design fields for each the lower and upper skin surfaces. Figure 18 visualizes the resulting thickness distribution for the two new reduced models. The illustration reveals that the decreasing accuracy of the optimization model trends to a wider area of increased component thickness. This time, the significantly increased stiffness of the skin component – due to the extended high skin thickness regions – also influences the spars and ribs near the kink and at the wing-fuselage intersection area.

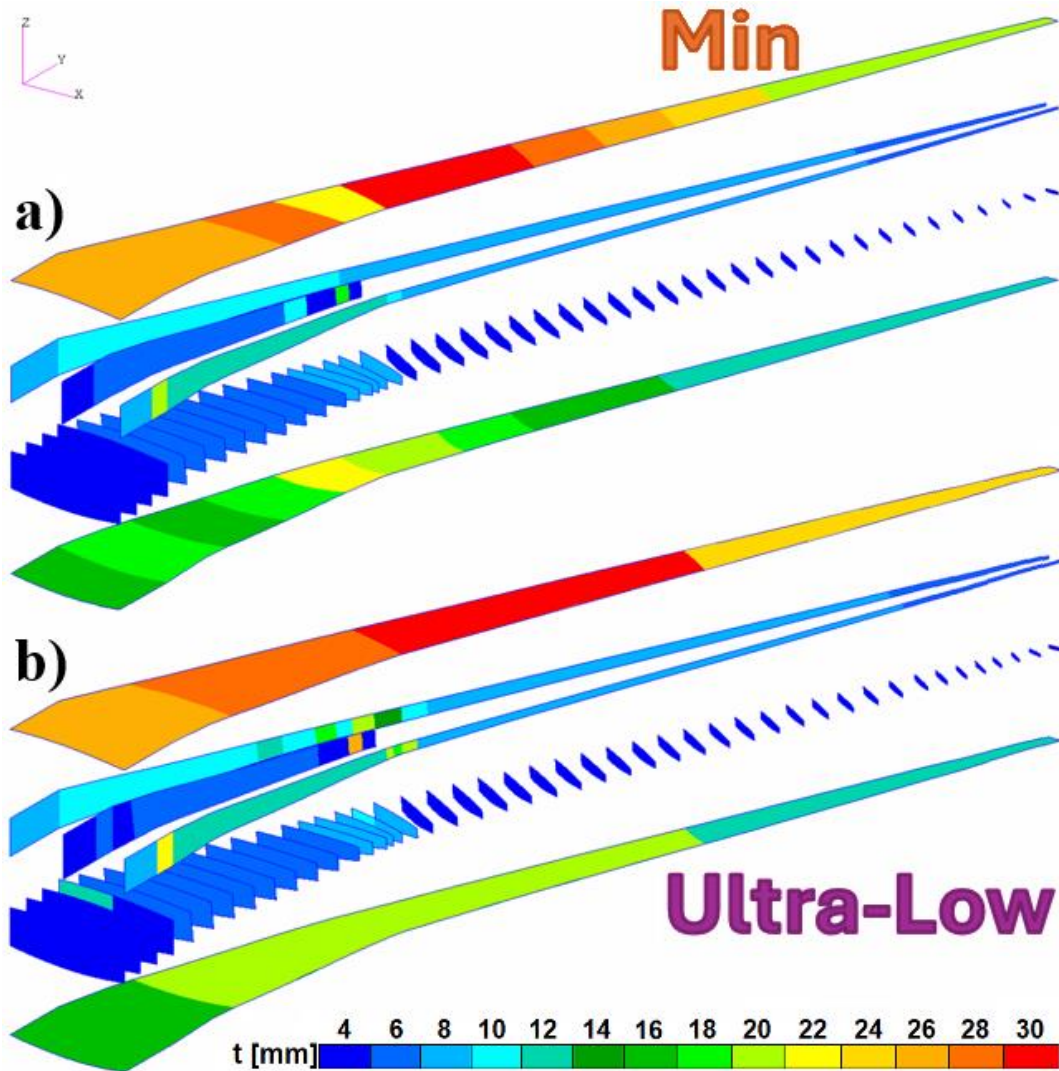


Figure 18: Resulting structural component thickness distribution of the main wing for the two even more reduced optimization model fidelity levels – exploded view.

The main results of the reduced fidelity models – all together with the former investigated fidelity models – are listed in Table 7. On this occasion, a three percent deviation ($3.3\ t$) exposes between the highest to the lowest fidelity level in the resulting operating empty mass. The same applies for the maximum bending moment and the first elastic Eigenfrequency. Due to the significantly increased stiffness, the vertical tip displacement is six percent lower and the twist deformation at the wing tip for the $1g$ -cruise condition is even ten percent less for the lowest fidelity level in comparison to the model with the highest fidelity.

Table 7: Main results comparison for all five different fidelity models.

Parameter	Ultra-Low	Min	Low	Mid	High
Operating Empty Mass [t]	132.8	131.8	130.6	130.1	129.5
Max. Bending Moment [10^7 Nm]	2.083	2.066	2.05	2.04	2.027
Tip z-Displacement (1g) [m]	2.59	2.65	2.70	2.74	2.76
Tip y-Rotation (1g) [deg.]	-4.80	-4.96	-5.21	-5.28	-5.35
1 st elastic Eigenfrequency [Hz]	1.004	0.994	0.987	0.980	0.977
Flutter speed of Mode 16 [m/s]	517	505	496	490	481

In case of the subsonic flutter check for the ultra-low-fidelity model, the damping curves of Modes 16 and 18 again show a crossing into the positive damping area. But this time, Mode 21 indicates flutter instead of Mode 19. In terms of the flutter speed for Mode 16, the analysis reveals a non-conservative trend with considerably higher lowest flutter speeds for the lower fidelity models. In case of the LamTA configuration, the flutter speed is far outside of the certifiable speed region and therefor a non-conservative flutter prediction might not be critical. But if in the early design phase of a new aircraft development, a structural optimization with too inaccurate design fields reveals a flutter case with a wrongly high flutter speed shortly after $1.15 \cdot V_D$, later at a more detailed phase of the development, the actual flutter case might occur at a lower speed and in the worst case within the certifiable stability envelope. Changes at the aircraft to prevent flutter are more and more costly the later they have to be incorporated into the design.

5 SUMMARY AND CONCLUSIONS

The purpose of this paper is to investigate the influence of the design field discretization within a structural optimization of the main wing of an aircraft on its aeroelastic assessment. To evaluate the effect, the preliminary aeroelastic structural design tool cpacs-MONA is used for the long-range aircraft developed within the DLR project LamTA. Firstly, a local refinement of the default design field discretization of cpacs-MONA has been applied, while keeping the wing topology and the FEM partition unchanged, to check if local effects coming from landing gear or engine attachment loads can be mitigated. It has turned out that the loads, the resulting structural mass, the stiffness – and therefore the resulting flight-shape – together with the flutter behavior for the investigated Low-, Mid- and High-fidelity optimization models only vary between one and three percent. So, the low fidelity level – one design field between two ribs – seems sufficient enough for the preliminary design of a new aircraft configuration to predict the flight-shape or to indicate the consequent primary mass of the wing. A model with an even lower fidelity – only four design fields for each side of the skin components – reveals, that the main results differ up to ten percent.

Regarding the flutter speed, the lower fidelity models show a non-conservative trend, where the lowest flutter speed elevate with decreasing fidelity of the optimization model discretization. In case of manufacturing of a real aircraft's wing, the high-fidelity and even the mid-fidelity resolution of the actual skin components to be build, might be too delicate and costly to produce.

And the flight-shape is the consequence of the manufactured jig-shape of the main wing together with its given elastic behavior and the imposed loads acting in the design-flight-point. It is very

important for the structural design team to find the correct jig-shape to exactly meet the desired optimum design-shape – showing the best cruise performance – to further reduce the climate impact of future aviation. Due to the fact that the flight-shape also depends on the wing loading conditions (actual aircraft mass, center-of-gravity location, amount of fuel in the wing-tanks), cpacs-MONA is also capable to predict the flight-shape at specific off-design-points or along the mission of an aircraft. So far cpacs-MONA supposes the jig-shape as given. It is planned to introduce the capability to give a desired flight-shape at a specific flight point and cpacs-MONA internally re-calculates the prerequisite jig-shape with the resulting stiffness of the wing to fit the aerodynamical optimum deformation.

Consequent next steps could be to investigate the influence of the design field resolution for a composite wing with introduced lamination parameter optimization and blending constraints or to incorporate high-fidelity CFD corrections for the loads analysis to better predict the desired flight-shape in cruise condition.

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