# DEFINITION OF A COMPREHENSIVE LOADS PROCESS IN THE DLR PROJECT ILOADS

W.R. Krüger, T. Klimmek

Deutsches Zentrum für Luft- und Raumfahrt, Institut für Aeroelastik
Bunsenstr. 10, 37073 Göttingen, Germany

## Summary

The determination of loads acting on the aircraft is one of the main tasks during aircraft development. The knowledge of loads is important for aircraft design, e.g. for the sizing of the airframe structure, and also for certification. The definition of realistic loads assumptions is important, as well as the generation of loads from simulation and experiment. DLR is involved in a large number of aircraft design activities, and operates a fleet of research aircraft; thus DLR requires in-depth expertise for the definition and the determination of relevant and crucial load cases.

The aim of the project iLOADS is the development of an internal DLR loads process, comprising expertise from different DLR institutes. The goal of the process is to strengthen the assessment capabilities of DLR with respect to the influence of loads on new aircraft configurations, and to support certification capabilities for the DLR aircraft fleet. The loads process will be investigated towards the influence of different analysis approaches on aircraft structural design, and it will be subject to verification and validation on different aircraft configurations.

The paper will give an overview of the background of the iLOADS project, as well as of the work performed in the project. The definition of the loads process as well as the implementations for different applications investigated in the project will be presented in more detail.

## 1. ILOADS: A COMPREHENSIVE LOADS PROCESS FOR DLR NEEDS

### 1.1. Background

To determine the loads acting on the aircraft is one of the main tasks during aircraft design. Wright and Cooper, [1], summarize the task as follows - „Aircraft are subject to a range of static and dynamic loads resulting from flight manoeuvres, ground manoeuvres and gust/turbulence encounters. These loads cases are responsible for the critical design loads over the aircraft structure and thus influence the structural design." Knowledge of the loads is thus required for design and structural sizing, for prediction of the performance, as well as for certification. Important are the definition of realistic load cases as well as the determination of loads in simulation and experiment.

DLR has a large number of activities in aircraft preliminary design and in the operation of a fleet of research aircraft, and thus requires in-depth expertise for the analysis of relevant and crucial load cases. Thus, DLR has need of an established comprehensive and well-founded loads process. At the same time, extensive knowledge exists in the various DLR institutes in numerous aspects concerning the field of loads analysis. This expertise covers pragmatic to high-end methods for both simulation and testing.

The DLR project iLOADS, „integrated LOADS analysis at DLR", answers to those requirements. The expertise in loads analysis is combined and integrated into a comprehensive loads process. Such a process has been formally defined, and global rules for analysis and documentation have been set. Selected numerical methods for loads analysis have been evaluated, and the loads process has been used for investigations on the influence of different analysis approaches on aircraft structural design. Finally, the process has been subject to verification and validation on different aircraft configurations, numerically as well as experimentally.

### 1.2. Project Goals and Technical Content

Two main goals of the iLOADS projects were defined:

- the definition, implementation and validation of a loads process tailored to DLR needs, and
- the support of the certification activities of the DLR fleet of aircraft.

The project was structured in four work packages. In the first work package, the loads process was defined and documented with respect to the DLR requirements. In the second work package, numerical simulations methods of varying complexity were compared, with a focus on aerodynamic methods, as well as on methods for the analysis of discrete gusts and for manoeuvre loads. In the third work package, different approaches for sizing of fuselage structures have been compared and validated with experimental data. In work package four, implementations of the loads process have been applied to different use cases - applications were the generation of preliminary design loads for a transport aircraft configuration, the numerical analysis of loads for an existing long-range aircraft, as well as the measurement of loads during flight testing on two aircraft, first on the structure of a sailplane, and second on the outer store of a high altitude research aircraft. The work of work packages two, three and four is summarized further down in the paper and described in detail in separate papers, see [2], [3], [4], [5], [6], and [7].

### 1.3. Partners

Partners in the project were the following institutes and units from the DLR aeronautics branch:

- the Institute of Aeroelasticity, Göttingen,
- the Institute of Aerodynamics and Flow Technology, Braunschweig,
- the Institute of Structures and Design, Stuttgart,
- the Institute of Composite Structures and Adaptive Systems, Braunschweig,
- the Institute of Flight System Technology, Braunschweig,
- DLR Flight Experiments, Oberpfaffenhofen,
- DLR Air Transportation Systems, Hamburg,
- the Institute of System Dynamics and Control, Oberpfaffenhofen, and
- the Institute of Materials Research, Köln.

### 1.4. Related Activities

Loads analysis plays a role in a number of running activities, both for application of loads analysis and for development of selected loads analysis methods.

In DLR, a loads process for conceptual design has been established and used in the projects VAMP and FrEACs [8]. Validation and application of approaches for gust loads analysis have been part of the iGREEN [9] and the ALLEGRA projects, including numerical investigations as well as wind tunnel experiments on a transonic gust generator in the transonic wind tunnel Göttingen, TWG-DNW [10]. The DLR-project Digital-X has focused on the application of CFD and complex structural models in aircraft design loops, also implementing an iterative process for loads and sizing [11].

Several projects of the German National Aeronautics Research Programme (Lufo), e.g. the Lufo 4 - projects M-FLY and FTEG, covered improvement and validation of loads analysis methods in an industrial context.

In the framework of EU projects, the FP7-project Smart Fixed Wing Aircraft (SFWA) included a work package dedicated to the loads analysis on passive and active wings, including loads alleviation strategies [12]. Reduced order methods and CFD-based gust analysis is the topic of the FP8-H2020 project AEROGUST [13].

Most projects concentrate on specific details of the loads analysis, on the application on design aspects, or on an automation of a loads process for MDO purposes. The DLR project iLOADS focuses in addition on the completeness and the quality of the loads process as such.

## 2. LOADS PROCESS

### 2.1. Definitions

The term "loads" is used in a wide context and with a variety of meanings, thus requiring a definition of the term as it will be used in the context of the paper.

**Loads** will be used to describe forces and moments acting on the aircraft structure, resulting from air pressure (lift, pressurization), mass forces (inertia, gravity), structural forces (elasticity) and other forces such as landing impact or thrust.

The word **loads process** will be used as follows, see also Figure 1:

(1) For given boundary conditions (e.g. flight conditions, certification requirements),

(2) for a given configuration (aircraft or component),

(3) loads on the structure shall be determined,

(4) with methods of adequate fidelity,

(5) the loads will be used for structural design, assessment of configurations or certification of aircraft.

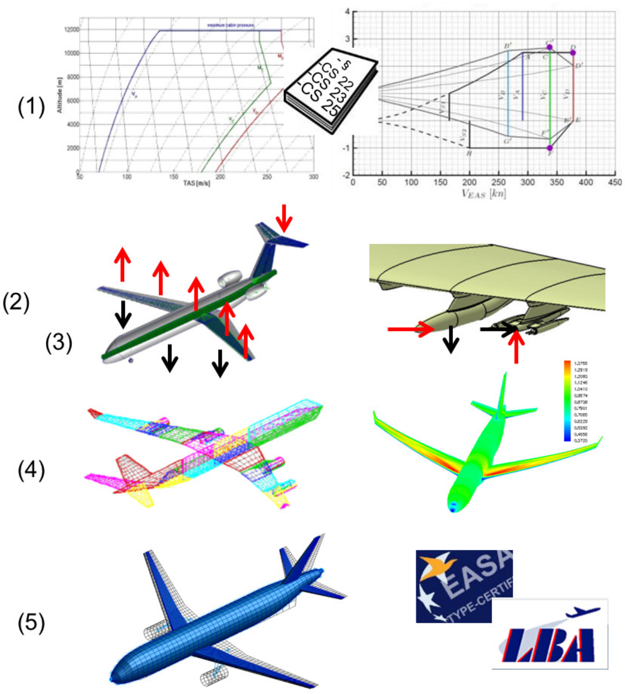


Figure 1: *Definition of the term "Loads Process"*

Frequently, the term load also is also used in the sense of cargo or additional equipment. While freight, of course, also inflicts mass forces on the aircraft, we will try not to get these connotations mixed up. Furthermore, the paper will concentrate on mechanical (structural) loads, electric loads will not be addressed; they are an important topic when designing an aircraft, but with little direct impact on the structural loads process.

"Classes" of loads are often combined in categories. A common classification differentiates between flight loads (manoeuvre loads, gust loads), ground loads (landing loads, ground manoeuvres), inertial loads (oscillations, vibrations), and special load cases (pressurization, bird strike, crash / ditching, fatigue).

A complete loads loop will consist of a large number of single analyses, potentially going into the thousands. This, consequently, requires a well-structured data management and a careful and thorough evaluation, condensation and interpretation of results to be able to perform reliable assessments.

## 2.2. Standard Literature

A number of publications cover the loads process and loads analysis methods. The books by Lomax [14], concerning structural loads analysis, and by Hoblit [15], covering gust analysis, are considered standard literature, as well as the book by Howe [16]. The textbook by Wright and Cooper [1] is concerned with the representation of the underlying physical effects. Important boundary conditions arise from certification and the respective specifications [17], [18]. The standard tasks of a loads process are well described in the often-cited article of Neubauer and Günther [19].

## 2.3. Requirements

Approaches for industrial loads analysis are dependent on aircraft size and type, regulations (CS-22 / CS-23 / CS-25), company size and company design philosophy. The DLR loads process is defined such that it addresses the specific DLR requirements. Criteria for the process are derived from the application scenarios. All tasks have in common that a great number of analyses has to be performed in a limited amount of time. Thus, the process hast to be **comprehensive for a given task**, and performed **with adequate fidelity**. The process has to be subject to a quality management under the following key topics - it must be possible to **understand** the approach, to **reproduce** all results, to **document** and to **review** process and results. The process has to be **maintained**, **availability of methods** as well as **operators** educated in the process is important.

The core process defined in the project consists of the following phases, see Figure 2:

- **loads case definition** phase, i.e. the definition of relevant load cases for analysis, and of requirements for the models to be used,
- **loads analysis** phase, i.e. the analysis of manoeuvre loads, gust loads, landing loads, special loads, etc,
- **loads post processing** phase, the creation of a loads database which can be processed according to the quantities needed, e.g. cut loads for evaluation or maximum nodal loads for sizing.

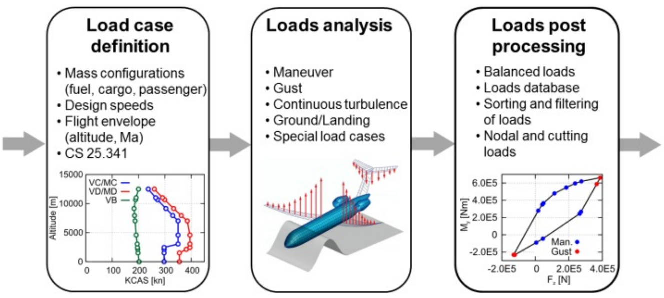


Figure 2: *Phases of the DLR loads process*

Specifications for the necessary analyses result from the operational requirements like the projected flight speeds and altitudes of the aircraft. A catalogue of load cases is defined depending on those boundary conditions. Load cases defined in this catalogue will then be addressed subsequently.

The calculation of loads is a wide field as the use of many different simulation tools depending on the load cases (manoeuvres, gusts, landing, bird strike, etc.) might be necessary. The agreement on a common nomenclature and on common interfaces for model data and result data is therefore essential and was part of the project.

The results of the analyses will be collected and used for the design and evaluation of configurations, for example for structural sizing and aircraft mass estimation. For quick representation and comparability of results, cut loads defined on loads reference axes were used. For sizing purposes of the wing structure, nodal loads were also available.

## 2.4. Aircraft Configurations

At the beginning of the project it was agreed to perform as many analyses as possible on a common reference configuration. For this purpose, the so-called DLR D150 configuration was available, an aircraft design similar to an A320 in size, see Figures 3 and 5 below. For the D150, data was available from previous DLR projects [20]. A structural design as well as aerodynamic data, both in the form of a Doublet Lattice Model (DLM) model and CFD data, could be used. The wing geometry used for CFD meshes corresponds to the DLR F-6 configuration [21]. The experimental structural investigations (see Section 4) were also based on the geometry and loads calculated for the D150 aircraft.

Furthermore, design loads data from two production aircraft could be used for comparison in the iLOADS project, first data taken from the VFW 614 design documentation, second data provided by Gulfstream Aerospace in the course of the certification of the HALO atmospheric research aircraft, operated by DLR [22].

## 2.5. Tools and Data Format

A number of different analysis tools have been used in the iLOADS project, depending on the application. Where necessary, details will be provided in the respective sections below. Commercial software packages used were the finite element codes ANSYS [23] and MSC.NASTRAN [24]. For CFD analysis, the DLR TAU code was employed [25]. Loads analysis was performed using MSC.NASTRAN and the DLR/Airbus development VARLOADS [26]. The DLR tool MONA (ModGen & NASTRAN) [27] was used for parametric modelling (ModGen) and sizing using the structural optimization routines of NASTRAN. For ANSYS, finite element models were set up by the DLR tools DELIS [28] and TRAFUMO [29], while sizing was performed using the commercial tool HyperSizer [30] or the DLR development S-BOT [28]. As much as possible, model definition and data exchange were performed in the CPACS format [31].

## 3. ANALYSIS OF DYNAMIC LOADS

In this work package, simulation methods for loads analysis were investigated. Focus was on the evaluation of different modelling levels of detail for aerodynamic analysis, and also for the analysis of manoeuvre loads, gust loads and landing loads. For those loads classes, a comparison of loads levels coming from dynamic analyses with loads derived from equivalent static load cases has been performed. Section 3 gives a summary of the activities in the work package. A comprehensive overview can be found in [2].

### 3.1. Aerodynamic Loads

Aerodynamic analyses in this work package were performed by the Institute of Aerodynamics and Flow Technology. Work was initially planned to be executed on the D150 configuration. It quickly showed that the wing geometry resulting from the preliminary design phase of that aircraft, and stored in the CPACS data, was not suitably for CFD analysis, as standard subsonic profiles have been used in that phase. It was thus agreed to use the geometry of the DLR F-6 configuration, very similar to the predesign wing but with a transonic profile, as the reference for aerodynamic investigations, see Figure 3.

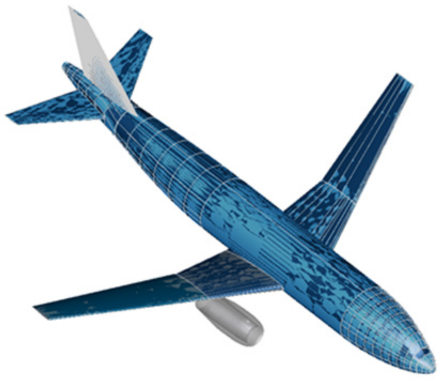

Figure 3: *Comparison of geometrical representations of the DLR D150 configuration using CATIA and CPACS*

The following aerodynamic tools were taken into consideration for the comparison of methods:

- LIFTING_LINE (a multi lifting-line approach, DLR) [32]
- VSAERO (3D-Panel Method, commercial: Analytical Methods) [33]
- TAU (3D-Navier-Stokes-Solver, DLR) [25]

It should be noted that the LIFTING_LINE and VSAERO-interfaces are currently restricted to configurations with wing and empennage only, consequently neglecting the fuselage. This fact was acknowledged in the discussion of the results.

An important step was the definition of assessment criteria for the calculation of aerodynamic parameters for loads analysis. The following quantities were selected as relevant:

- global aerodynamic coefficients, especially lift coefficient $C_A$ and moment coefficient $C_{My}$,
- distribution of local aerodynamic coefficients, especially of $C_a$ and $C_{my}$,
- gradients of aerodynamic coefficients with respect to angle of attack, especially $\Delta C_a / \Delta\alpha_{tot}$ und $\Delta C_{my} / \Delta\alpha_{tot}$.

As an example, Figure 5 shows the span-wise distribution of lift $C_l$ and moment $C_m$ as well as the local gradients with respect to the total angle of attack $\alpha_{tot}$ at the transonic Mach number of $M$ = 0.75. The small absolute deviations also confirm the agreement of the (subsonic) compressibility corrections implemented in both tools. The good agreement for the $C_l$ gradients could also be shown for wing-tail configurations. While the span-wise distribution of $C_{my}$ shows deviations in the absolute values, but still with similar trends, very significant deviations are observed for the gradients with respect to $\alpha_{tot}$, which is again due to different sensitivities of the centre of pressure between the multiple lifting-line method and the panel method.

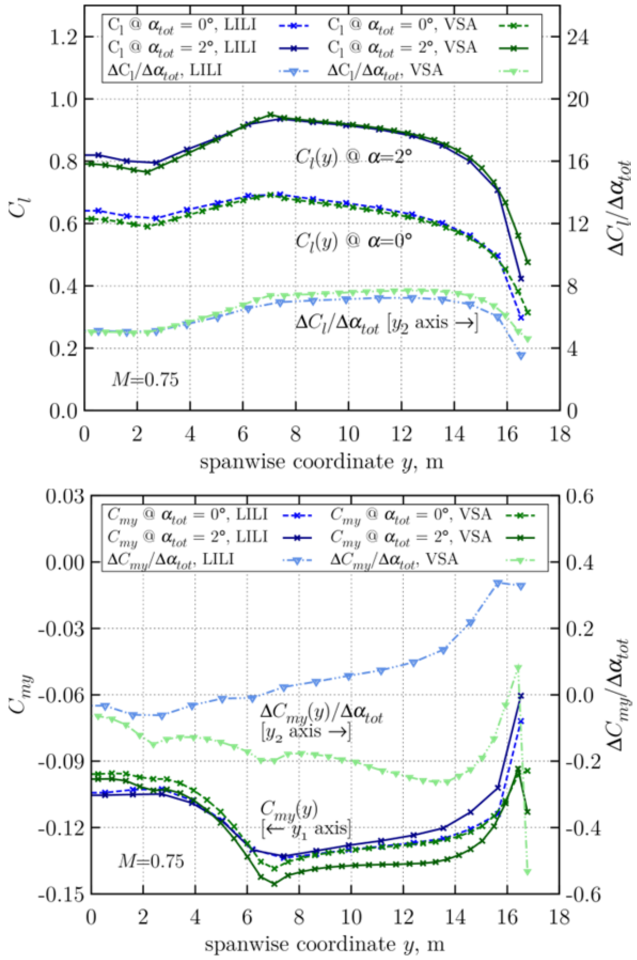


Figure 4: *Comparison of* $C_l$ *and* $C_m$ *distributions between LIFTING_LINE (LILI) and VSAERO (VSA)*

This has to be carefully checked during tool selection, when being applied for load analysis and prediction, but also in the context of trimming of the overall aircraft configuration.

### 3.2. Gust Loads

For the definition of discrete gust loads, two approaches are common, the so-called 1-cosine-gust, solved with a dynamic analysis, and the so-called Pratt gust, a steady approximation of the dynamic gust phenomenon. While for transport aircraft certified according to CS-25 the dynamic simulations are required, the Pratt gust is still much in use in conceptual and preliminary aircraft design and can be used for aircraft certification according to CS-23.

Goal of the activity was to obtain an assessment of the fidelity and an understanding of the differences between the approaches. The investigations described in the following paragraphs have been undertaken by the Institute of Aeroelasticity, using MSC.NASTRAN.

The Pratt equation is based on the following assumptions:

- the aircraft is rigid,
- the flight speed remains constant,
- the aircraft flies in a steady and trimmed state before hitting the gust,
- the only degree of freedom is heave,
- lift is generated by the wings, lift generated by fuselage and empennage can be neglected,
- the gust speed is constant over the wing span and parallel to the vertical axis.

Pratt derived his equation for a gust length of 25 times the chord length. For a simple wing example performed in iLOADS, the load factor generated by the Pratt equation proved indeed to be identical to the maximum load factor of a 1-cosine-gust.

For a complete aircraft, the result of such a comparison depends on the gust length. For the D150 configuration, the maximum load factor of all gust lengths fits well with the Pratt assumption, see Figure 5 for the example of a vertical gust. However, when the gust length excites a natural frequency of the aircraft, e.g. the first wing bending mode, maximum load factors can be higher than predicted by the Pratt equation. Such an effect could be seen on the D150 configuration for lateral gust loads.

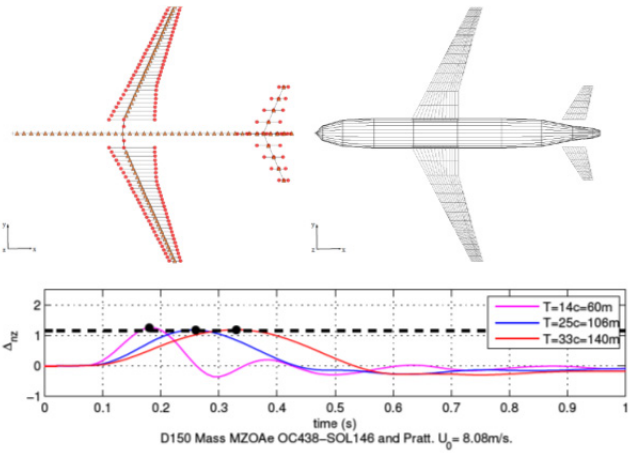


Figure 5: *top: condensed structural model and DLM model of DLR-D150 used for gust analysis; bottom: comparison of Pratt gust and 1-cos-gusts for different gust lengths*

## 3.3. Manoeuvre Loads and the Effect of a Flight Control System on Aircraft Dynamic Loads

Many manoeuver loads can be represented as so-called trim cases. One question is whether a (steady) trim case can correctly represent all loads arising in a dynamic manoeuver. In the work package, a dynamic yaw and a dynamic roll manoeuvre have been investigated by the Institute of System Dynamics and Control.

**Dynamic yaw:**

According to paragraph CS 25.351, the dynamic yaw manoeuver is defined in four phases:

a. In the cockpit, the rudder is rapidly pushed into the limit stop while the aircraft is in horizontal flight.

b. The aircraft yaws and will over-swing into a maximum yaw angle.

c. After the transient is damped out, the aircraft will fly in steady slip with full rudder.

d. From this condition, the rudder is rapidly brought into the normal position.

A flight control system has to be considered.

Rather than performing a dynamic simulation, representative trim calculations can be performed. Phases a), c) and d) can be well represented by a trim calculation. Phase b) is highly dynamic, and loads from overswing can only be calculated correctly by a dynamic simulation, see Figure 6. If a yaw damper is used, it has a significant influence on the overswing loads, as can be seen in Figure 6, where different colours represent different yaw damper settings.

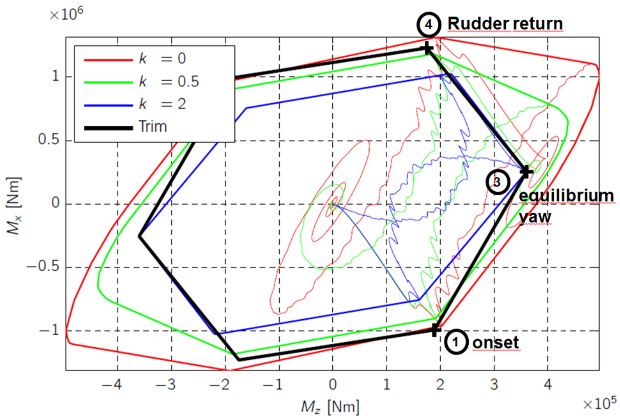


Figure 6: *Yaw manoeuvre: resulting moments for dynamic simulation and representative static analyses [2]*

**Dynamic Roll:**

Maximum loads from a dynamic roll manoeuver heavily depend on the pilot model used. A pilot model is necessary, as a constant load factor during the manoeuver, as required by the regulations, cannot be obtained without such a model.

The steady roll and the two accelerated roll conditions can be specified as trim conditions. The resulting correlated load envelopes for right and left roll are depicted in Figure 7. The trim results compare well to the dynamic solution, except for the onset condition. This can be attributed to the "structural" dynamic overswing during the abrupt initialization of the roll manoeuvre. The resulting sharp peaks for the accelerated rolling conditions 1 and 3 are due the very aggressive application of the ailerons. The remaining differences are a consequence of the inability to hold the appropriate load factor.

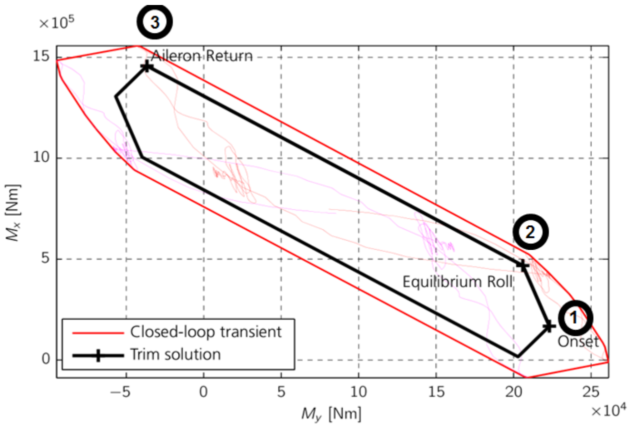


Figure 7: *Correlated loads for roll manoeuvre dynamic simulation compared to trim results.*

### 3.4. Ground Loads

There are two approaches for the calculation of aircraft ground loads which are widely employed, empirical methods and simulation-based methods. Empirical methods are statistical approaches, based on data of existing aircraft. There are three major formulations for this method which are given by Lomax [14], Howe [16] and Roskam [34]. These formulations determine the ground loads on each landing gear by first calculating equivalent dynamic loads from empirical equations and then multiplying those equivalent ground loads on each landing gear with load factors according to certification requirements, usually 1.5.

More realistic dynamic landing loads (sometimes called “rational loads”) can be calculated by time domain simulation of landing impacts. Cases frequently used are the so-called “3-Wheel Level Landing Case” according to CS 25.479 and the “2-Wheel Tail-Down Landing Case” (CS 25.481). Multibody models of aircraft and landing gear are used for simulation.

In the work package, results from the empirical approaches and from the simulation have been compared by the Institute of Aeroelasticity to design data from the VFW 614 aircraft as used by DLR until 2012, see Figure 8. Results of interest for the validation are the main landing gear landing (MLG) loads.

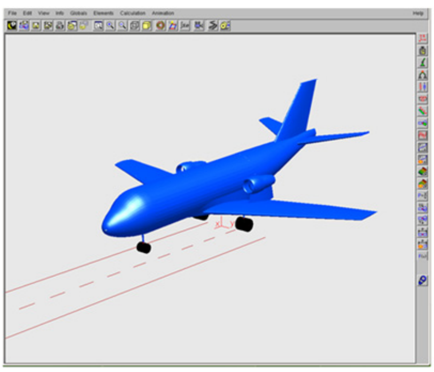

Figure 8: *Multibody model of VFW 614 aircraft used for ground loads analysis*

For the 2-wheel landing case, the estimated loads from all empirical methods deviate no more than 5% from the values calculated by the aircraft manufacturer. The difference of the multibody simulation to the industrial data was in the same range, see Figure 9.

| Landing Loads Determination Method | Main Landing Gear Attachment Loads, Fz (N) |
|---|---|
| VFW614 Reference Data | 117,522 |
| Empirical | 124,989 |
| Simulation (MBS) | 113,082 |

Figure 9: *Comparison of different approaches for analysis of landing loads*

For the 3-wheel landing case, however, the empirical methods either cannot be applied or give loads which are considerably off. The 2-wheel landing (not taking the nose landing gear into consideration) gives higher loads than the 3-wheel landing case. In addition, the VFW 614 has a conventional landing gear configuration. It may thus be concluded that the empirical methods investigated are capable of giving good estimates for maximum vertical landing loads, whereas for more realistic cases, time domain simulation, e.g. using multibody simulation, gives more reliable results. The same is true for unconventional landing gear or aircraft configurations, where statistical methods cannot give reliable results because of the missing data base.

## 4. LOADS AND STRUCTURAL DESIGN

Goal of the work concerning loads and structural design was the use of results from the loads analysis for the design for aircraft structures and the assessment with respect to strength, stability, crash behaviour and fatigue. A more detailed description of the work can be found in [3] and [6].

### 4.1. Realistic Loads Assumptions for the Design of Aircraft Structures

In the project, the capabilities for the design of structures, here focused on fuselage design, were improved. For the D150 configuration, loads and a global structural design were available. However, those loads were defined on the loads reference axis, thus questions concerning a valid use of those loads for sizing of fuselage structures arise.

The geometry of the fuselage model, as well as the loads, are given in the CPACS format. The definition of the structure includes the skin with discrete reinforcements (stringers, frames), pressure bulkheads, PAX and cargo floor structure, structural coupling regions to wing and empennage models. Further considerations include materials data (isotropic, orthotropic), layered compositions, as well as arbitrary profile cross sections with arbitrary wall thickness.

Some loads cases deliver local loads to the structure. One example are loads from the landing impact. Here, global structural models will not be sufficient to capture the effects, and detailed representations of connections between components, e.g. of the wing-fuselage intersection or the wing-empennage intersection, are required. The Institute of Composite Structures and Adaptive Systems extended its model generator DELIS to create representative finite element models of those areas, see Figure 10.

In addition, the activities by the Institute covered comparisons of the potential difference in structural sizing when using equivalent static load cases vs. dynamic load cases (as described in Section 3 for gust loads, landing loads and manoeuvre loads).

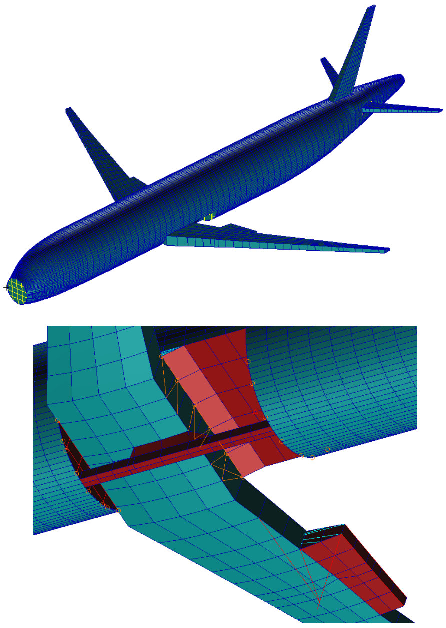

Figure 10: *Full aircraft finite element model and detailed coupling region of wing-fuselage intersection*

### 4.2. Realistic Loads Assumptions for the Design of Components

Goal of this work package was the development of a procedure to calculate realistic loads for a fuselage panel on a full aircraft model and to use those loads for experimental investigations on test panels.

As stated above, loads given for the D150 configuration were defined on the loads reference axis. Thus, different methods for the transfer of global loads, i.e. shear, moment and torque given for selected points, to the distributed fuselage structure, i.e. the panels, have been developed and compared. The Institute of Structures and Design calculated such loads on an airframe model in the classical metallic stringer / frame design for ANYSY, built up using the DLR TRAFUMO tool, and sized by S-BOT+ as the sizing engine. For a 1g flight point, the resulting loads in a fatigue-critical area on the top of the fuselage have been derived, see Figure 11.

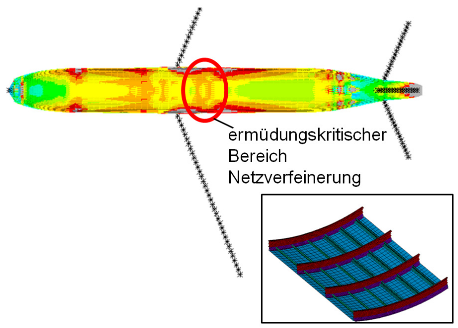


Figure 11: *Stress distribution in top fuselage at +1g flight case; red circle: fatigue-critical area*

These loads were then passed to the Institute of Materials Research, where the test on a bi-axial test rig was performed.

### 4.3. Realistic Loads Assumptions for Tests of Structures and Materials

The next step in the investigation was the experimental study of crack propagation for a representative fuselage section in a bi-axial test rig at the Institute of Materials Research.

The results of the loads analysis described above (see Figure 11) were evaluated for the definition of test rig loads. The stress from the simulation was taken as maximum stress for the experiment. To include stochastic effects a loads ratio of R=σmax/σmin=0,1 was assumed for the fatigue test. This ration loads to a critical fatigue state fast crack propagation.

The design of the bi-axial test specimen and of the forces to be applied in the experiment was performed using the finite element (FE) simulation, see Figure 12, with the software ANSYS. In the FE model a crack can be included.

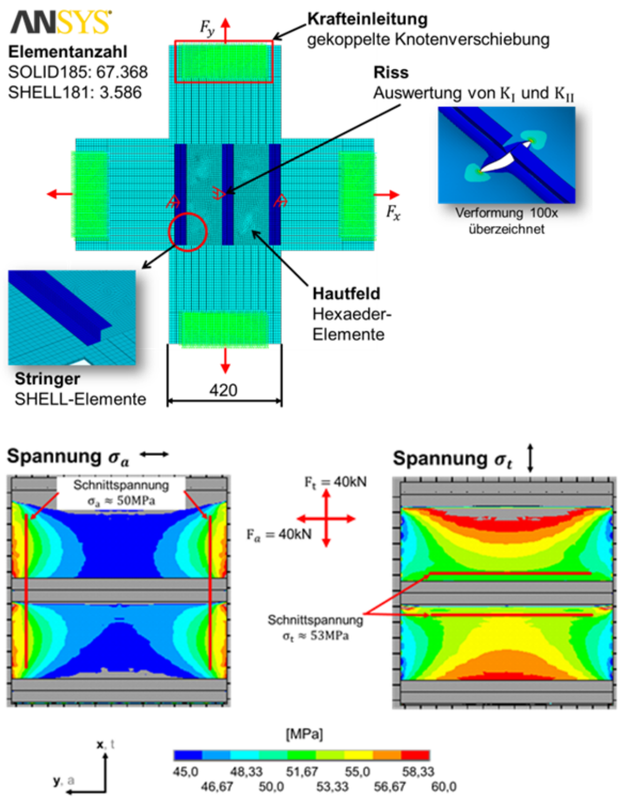


Figure 12: *FE-Model and cut loads for a bi-axial test specimen*

The test specimen was equipped with strain gauges in XY directions; furthermore, an optical system for deformation measurements was used. In a first experiment, the probe was tested without a crack with different load rations and forces up to 80 kN.

Optical measurements were employed at different force levels to compare simulation results to test results. In a second step, a notch was introduced across stringer and skin in the middle of the panel. A crack developed which was monitored to observe the speed and the direction of the crack growth.

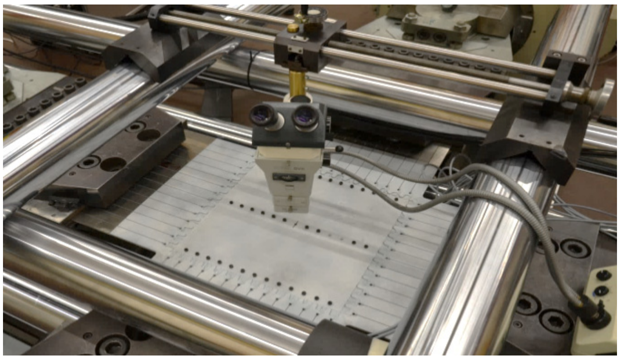

Figure 13: *Test specimen in bi-axial test rig.*

It could be shown that simulation can be used for analysis of complex structures. In the future, the way can be gone "backwards" - with material data and standard test specimen crack propagation and resulting life time of complex structures can be predicted by numerical (finite element) simulation.

In a second test, the Institute of Composite Structures and Adaptive Systems used a fuselage panel to validate their structural optimization process. Special focus was on the prediction of the buckling behaviour under loads.

The panel test was performed at the buckling test rig of the Institute. Next to strain gauges, two deflection sensors and two optical measurements systems (ARAMIS) were used for data acquisition. The ARAMIS systems covered the complete front side and most of the back side of the panel.

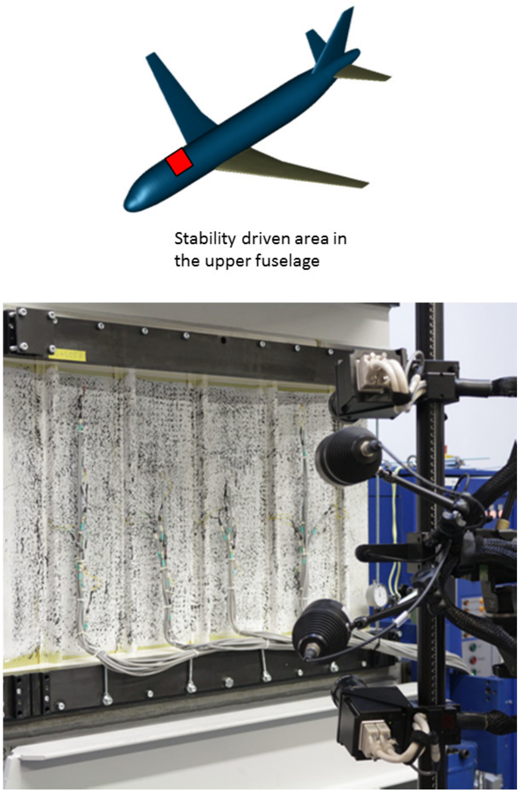


Figure 14: *Region of interest on the aircraft fuselage and test setup for buckling test on panel*

The respective FE simulation model is implemented using the Software Abaqus [35]. It consists of linear shell elements of 6 mm size for the skin and the stringers. The top and bottom of the panel have fixed, the sides have free boundary conditions.

The buckling loads of the experiment are well represented in the simulation. The difference between simulation and experiment are 6.6% for the first and 3.4% for the second mode. For all modes, the buckling patterns and the global stiffness distribution of the numerical model fits well with the experimental result, see Figure 15.

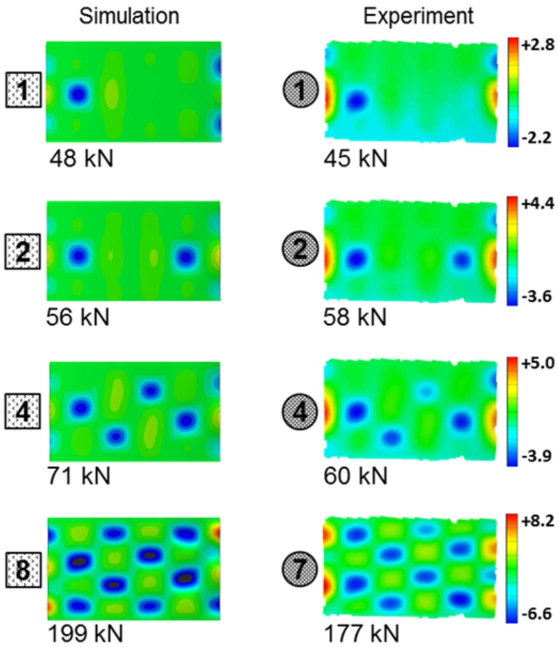


Figure 15: *Radial displacement and loads for different buckling patterns*

## 5. USE CASES: FROM CONCEPTUAL DESIGN TO FLIGHT TESTING

The different implementations of the loads process were applied to four different applications, so-called "use cases" - a pre-design study, the generation of a loads envelope for a large long range business jet, numerical analysis and test flight of an outer wing store, and loads measurements on a sailplane. Details to the activities can be found in [4], [5], and [7].

### 5.1. Loads Analysis Process in Pre-design Disciplinary Modules

The first use case was the implementation of a loads process for overall aircraft pre-design applications. A loads loop for pre-design was implemented in the RCE environment by DLR Air Transportation Systems. Focus was on an automated process for early design and on robustness of the process. All modules were based on CPACS, and TiGL geometrical kernel, any valid CPACS file can be analysed, and main physics effects captured.

The target of these activities was to be able to perform large trade studies. Multiple coupling schemes for miss-matching topologies, as they are needed for coupling purposes, e.g. for fluid.-structure-coupling, were evaluated. In iLOADS, the influence of aero-structural effects on sizing aircraft flexibility, and thus on performance, were of central interest.

Investigations were performed on the D150 model, see Figure 16. Analysis starts from an initial overall aircraft design (OAD) synthesis model. The loads are calculated for sizing of the airframe, a resulting deformation of the aircraft is calculated and used as input for a new loads loop. After convergence, a performance analysis is executed.

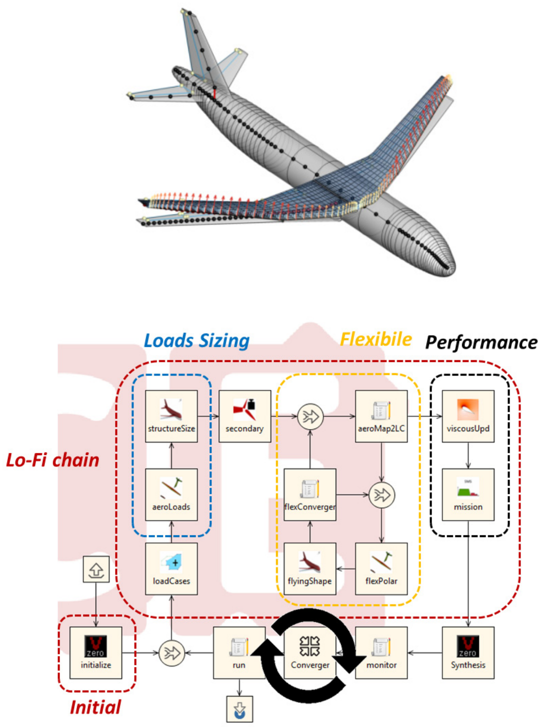


Figure 16: *D150 pre-design model and RCE-based analysis loop*

While the loop was tested for a conventional aircraft configuration, the final goal is to establish such a process for unconventional configurations, e.g. strut braced wings or box-wing configurations, see Figure 17, where design trends can only be reliably predicted when taking elastic deformations into account.

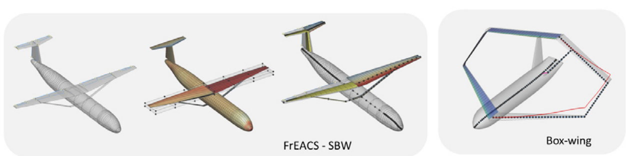


Figure 17: *Goal: reliable loads for unconventional configurations at preliminary design*

## 5.2. Loads Analysis on a High Altitude Research Aircraft

The high altitude research aircraft HALO, a Gulfstream G550, is operated by DLR to provide a high performance vehicle for atmospheric research. Test equipment can be placed in stores attached to the wings or fuselage. DLR has to implement and certify these modifications depending on the specific mission. From certification activities of the aircraft for the use with outer wing stores, DLR was provided by Gulfstream Aerospace (GAC) with loads envelopes relevant for the placement of those attachments.

The second use case in iLOADS was the task to simulate those load cases with the DLR loads process and with an aircraft model coming from the DLR parametric design process. The design process used by the Institute of Aeroelasticity was the so-called MONA process, where a parameterized aircraft model with global structural representation (finite element model), aerodynamic (DLM) model, and a mass model including various mass configurations was set up. Sizing loads came from the data provided by GAC. A condensed model of the aircraft was used for loads analysis, see Figure 18.

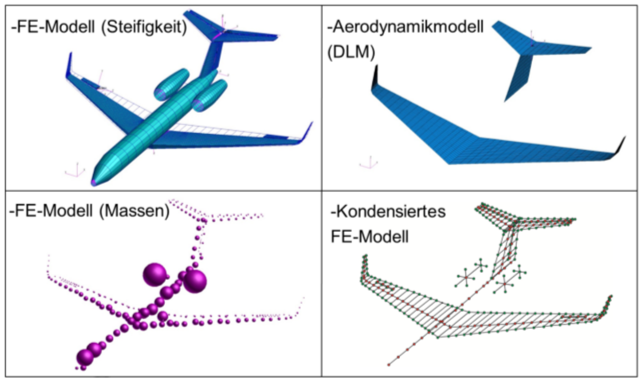


Figure 18: *Aircraft model of G550 HALO from MONA process used for loads analysis*

Loads on wings, fuselage and empennage were compared to the values given by GAC. First evaluations showed good agreement for most parts of the aircraft structure, differences can be see mainly for the empennage, where the modelling should be improved, e.g. by updating the model with information gathered from ground vibration testing performed by DLR on the HALO in 2010.

The HALO model was then used to generate realistic loads for the outer wings store, the so-called PMS (particle measurement system) - carrier, see Figure 19.

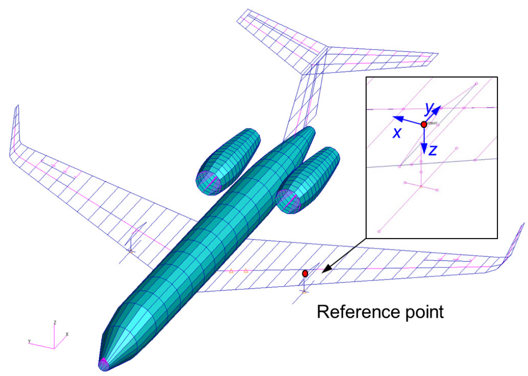


Figure 19: *Simulation of loads at PMS attachment point*

For typical gust cases at Ma=0.85 at an altitude of 8500 m displacements and accelerations of the attachment point of the PMS carrier were generated. These values were later used for the hardware test of the PMS on the vibration table MAVIS at the Institute of Aeroelasticity.

### 5.3. Loads Measurements on the HALO PMS-Carrier in Flight Tests

The PMS carrier tested is a DLR development for carrying large measurement equipment for atmospheric research under the wings of the HALO aircraft. For certification, it has to be ensured that the maximum attachment loads of the carrier to the wing specified by GAC will not be exceeded under any loading conditions or the PMS carrier. A numerical model of aircraft and carrier has been built up which has to be validated by loads measurements in flight.

First, loads were calculated for the carrier for a representative gust by the Institute of Aeroelasticity. The PMS carrier was equipped with strain gauges and accelerometers to measure vibrations and cut loads at close to the attachment points. The set-up was first tested on the MAVIS vibration table and later installed on the HALO aircraft, see Figure 20. For the data acquisition, a decentralized system, fitting into the central tube of the PMS carrier, was qualified for the flight tests.

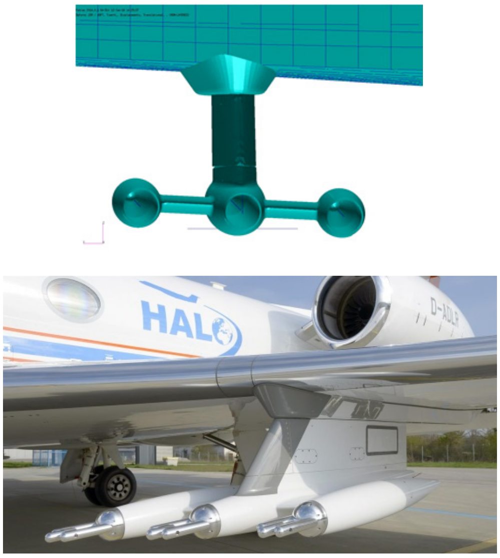


Figure 20: *PMS carrier, simulation model and hardware*

In five flights, a large number of manoeuvres could be flown, and an extensive amount of data was recorded. First evaluations showed promising agreement between numerical and experimental data, but the main amount of evaluation has yet to be done and is part of the follow-on DLR project KonTeKst ("Konfigurationen und Technologien für das emissions- und lärmarme Kurzstreckenflugzeug", 2016-2018). The same data set was used for online identification of the aeroelastic model of the aircraft, see [5].

### 5.4. In-Flight Measurements of Loads on the Discus-2c Sailplane

The Discus-2c is a research aircraft used at DLR as a reference aircraft to validate new in-flight identification methods and to benchmark the performance of new glider designs. A special feature of the Discus-2c of DLR is its generous storage space for measurement electronics. The fuselage and the wings are fitted with over a dozen strain gauges, designed to measure the load exerted during various flight conditions. The starboard wing also houses a fibre Bragg grating with glass fibre running along the spar. This system is used to make extremely precise measurements of wing deflection, see [36], and Figure 21.

In the project iLOADS, an approach for in-flight loads measurements has been developed by the Institute of Flight System Technology. An extensive calibration and flight testing programme was performed. On the ground, the deflection of wings and empennage under loads were measured with laser-interferometers at selected points. Strain gauges and Bragg grating were calibrated. In subsequent flight tests, manoeuvres for longitudinal and lateral motion were performed at 396 test points in 22 flights.

With the experimental data, a real-time model for flight simulation was identified and approaches for the estimation of flight loads were developed. An integrated modelling approach takes interaction between rigid body flight mechanics and structural dynamics into consideration.

Simulations with the identified model show the quality of the identified model and can clearly illustrate the influence of elastic vibration modes on the quality of the simulated aircraft response.

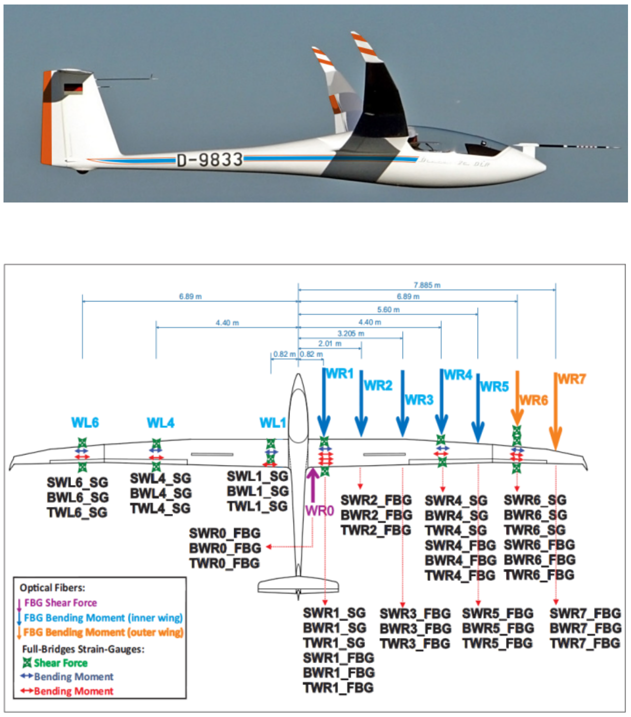


Figure 21: *Discus-2c in flight and positions of calibrated sensors for loads measurements*

## 6. SUMMARY AND OUTLOOK

In the iLOADS project, a comprehensive DLR-internal loads process was established. The loads loop profits from extensive know-how of the DLR institutes in various field of loads analysis from numerical simulation, experimental validation to flight testing. In the project, numerical methods were investigated, experiments on test rigs were performed, and in-flight loads measurements were conducted.

Work continues in several DLR projects, with a focus on component loads including high lift, an automated loads loop for multidisciplinary analysis using high fidelity methods, and applications of the loads process for various conventional and unconventional configurations.

## 7. ACKNOWLEDGEMENTS

The authors would like to thank all members of the project team for their dedication and commitment, and namely Thiemo Kier, Martin Geier, Per Ohme, Thomas Klimmek, Dieter Kohlgrüber, Julian Schwinn, Kristof Risse, Vega Handojo, Sunpeth Cumnuantip, and Julian Sinske for their contributions to this paper. The authors explicitly refer to their papers describing all activities in more detail. Those publications have been mentioned in the text and are listed in the list of references below. The authors also thank the DLR flight test department and the programme directorate for the support of the project and specifically the flight test campaigns.

## 8. LITERATURE

[1] Wright, J.R., Cooper, J.E. (2008): Introduction to Aircraft Aeroelasticity and Loads. Wiley Aerospace Series.

[2] Cumnuantip, S., Kier, T., Risse, K., G. Pinho Chiozzotto (2016): Methods for the Quantification of Aircraft Loads in DLR-Project iLOADS. Deutscher Luft- und Raumfahrtkongress 2016, Paper Nr. 0145. Braunschweig.

[3] Geier, M., Kohlgrüber, D., Schwinn, J., Breitbarth, E. (2016): Definition und Anwendung eines Lastenprozesses zur Ableitung realistischer Bauteiltests im DLR-Projekt iLOADS. Deutscher Luft- und Raumfahrtkongress 2016, Paper Nr. 0219, Braunschweig.

[4] Klimmek, T., Ciampa, P.D., Handojo, V., Ohme, P., Preisighe Viana, M.V. (2016): Aircraft Loads - An Important Task from Pre-Design to Loads Flight Testing. Deutscher Luft- und Raumfahrtkongress 2016, Paper Nr. 0223, Braunschweig.

[5] Sinske, J., Handojo, V., Buchbach, Ralf, Jelicic, G. (2016): HALO Flugtest mit instrumentierten Außenlasten für Aeroelastik- und Lastmessungen im DLR Projekt iLOADS. Deutscher Luft- und Raumfahrtkongress 2016, Paper Nr. 0276, Braunschweig.

[6] Schwinn, J., Kohlgrüber, D., Breitbarth, E., Besel, M. (2016): Biaxiale Versuche an rumpfstrukturnahen Proben mit realistischen Lastannahmen. Deutscher Luft- und Raumfahrtkongress 2016, Paper Nr. 0154, Braunschweig.

[7] Ohme, P., Raab, C. Preisighe Viana, M.V. (2016): Lastenmessung im Flugversuch und Entwicklung echtzeitfähiger Simulationsmodelle. Deutscher Luft- und Raumfahrtkongress 2016, Paper Nr. 0052, Braunschweig.

[8] Pfeiffer, T., Moerland, E., Böhnke, D., Nagel, B., Gollnick, V. (2014): Aircraft Configuration Analysis Using a Low-Fidelity, Physics Based Aerospace Framework under Uncertainty Considerations. Proc. 29th Congress for the Aeronautical Sciences, St. Petersburg, Russia.

[9] Krüger, W.R., Klimmek, T., Liepelt, R., Schmidt, H., Waitz, S., Cumnuantip, S. (2014): Design and aeroelastic assessment of a forward-swept wing aircraft. CEAS Aeronautical Journal, 5 (4), pp. 419-433. Springer Vienna. DOI: 10.1007/s13272-014-0117-0.

[10] Neumann, J., Mai, H. (2013): Gust response: Simulation of an aeroelastic experiment by a fluid-structure interaction method. Journal of Fluids and Structures 38, pp. 290-302, April 2013. DOI: 10.1016/j.jfluidstructs.2012.12.007.

[11] Leitner, M., Liepelt, R., Kier, T., Klimmek, T., Müller, R., Schulze, M. (2016): A Fully Automatic Structural Optimization Framework to Determine Critical Design Loads. Deutscher Luft- und Raumfahrtkongress 2016, Paper Nr. 0186, Braunschweig

[12] Krüger, W.R., Berard, A., De Breuker, R., Haydn, K., Reyes, M. (2016): Adaptive Wing: Investigations of Passive Wing Technologies for Loads Reduction in the CleanSky Smart Fixed Wing Aircraft (SFWA) Project. GREENER AVIATION 2016 - Brussels (BELGIUM)-October, 11th to 13th, 2016.

[13] AeroGust (Aeroelastic Gust Modelling). http://www.aerogust.eu. Last visited 09-09-2016.

[14] Lomax, T.L. (1996): Structural Loads Analysis Theory and Practice for Commercial Aircraft Structural Loads Analysis: Theory and Practice for Commercial Aircraft. AIAA Education Series, Washington.

[15] Hoblit, F.M. (2001): Gust Loads on Aircraft: Concepts and Applications. AIAA Education Series, Washington.

[16] Howe, H. (2004): Aircraft Loading and Structural Layout. AIAA Education Series, Washington.

[17] Federal Aviation Administration, Airworthiness standards (2010): Transport category airplanes, FAA, 14 CFR Part 25.

[18] European Aviation Safety Agency, Certification Specifications for Large Airplanes CS-25, ED Decision 2010/013/R (2010).

[19] Neubauer, M., Günther, G. (2000): Aircraft Loads. RTO/AVT Lecture Series on “Aging Aircraft Fleets: Structural and Other Subsystem Aspects”. RTO-EN-015-09.

[20] Moerland E., Zill T., Nagel B., Spangenberg H., Schumann H., Zamov P. (2012): Application of a distributed MDAO framework to the design of a short- to medium-range aircraft. 61th German Aerospace Congress (DLRK), Berlin, Germany.

[21] Brodersen, O., “Drag Prediction of Engine-Airframe Interference Effects Using Unstructured Navier-Stokes Calculations, Journal of Aircraft, Vol. 39, No. 6, 2002.

[22] DLR-Flugzeugflotte: http:// http://www.dlr.de/dlr/desktopdefault.aspx/tabid-10203/.
Last visited 11.09, 2016.

[23] ANSYS: http://www.ansys.com/Products/Structures
Last visited 12-09-2016.

[24] MSC.NASTRAN:
http://www.mscsoftware.com/de/product/msc-nastran
Last visited 12-09-2016.

[25] Gerhold, T., “Overview of the Hybrid RANS Code TAU,” MEGAFLOW—Numerical Flow Simulation for Aircraft Design, edited by Kroll, N. and Fassbender, J. K., Vol. 89 of Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Springer, Berlin and

Heidelberg, Germany, 2005, pp. 81–92.

[26] Hofstee, J., Kier, T., Cerulli, C. and Looye, G., "A variable, fully flexible dynamic response tool for special investigations (VarLoads)," International Forum on Aeroelasticity and Structural Dynamics, 2003.

[27] Krüger, W.R., Klimmek, T., Liepelt, R., Schmidt, H., Waitz, S., Cumnuantip, S. (2014): Design and aeroelastic assessment of a forward-swept wing aircraft. CEAS Aeronautical Journal, December 2014, Volume 5, Issue 4, pp 419–433.

[28] Führer, T.; Willberg, C.; Freund, S.; Heinecke, F.: Automated model generation and sizing of aircraft structures, Aircraft Engineering and Aerospace Technology: An International Journal, Vol. 88 Iss: 2, pp.268 – 276.

[29] Scherer, J; Kohlgrüber, D.; Dorbath, F.; Sorour, M.: A Finite Element based Tool Chain for Structural Sizing of Transport Aircraft in Preliminary Aircraft Design, DLRK 2013, Stuttgart, DocumentID: 301327

[30] HyperSizer: http://hypersizer.com/
Last visited 12-09-2016.

[31] German Aerospace Center (DLR): CPACS – A Common Language for Aircraft Design.
https://software.dlr.de/p/cpacs/home/
Last visited 12-09-2016.

[32] Horstmann, K.-H., "Ein Mehrfach-Traglinienverfahren und seine Verwendung für Entwurf und Nachrechnung nichtplanarer Flügelanordnungen", Ph.D. Dissertation, Technical University of Braunschweig, Braunschweig, Germany, 1987; see also: Tech. Rep. FB 87-51, DFVLR, Braunschweig, Germany, 1987.

[33] VSAERO: http://www.ami.aero/software-computing/amis-computational-fluid-dynamics-tools/vsaero/
Last visited 12-09-2016.

[34] Roskam, J., Airplane Design Part IV: Layout Design of Landing Gear and Systems. Roskam Aviation and Engineering Corporation, Kansas, 1986.

[35] Abaqus: http://www.3ds.com/de/produkte-und-services/simulia/produkte/abaqus/
Last visited 09-11-2016.

[36] Discus-2C DLR. http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10203/339_read-9181/#/gallery/8791. Last visited 09-09-2016.