DIGITAL INDUSTRIES SOFTWARE

Aircraft structural design and analysis

Breaking silos between engineering teams to achieve sustainable aviation

Executive summary

Moving from the fossil fuel powered aviation to the next-generation aircraft with multiple energy carriers and architectures constitutes a massive challenge but is required to stay competitive. Future airframes will come equipped with disruptive technologies like hybrid-electric and hydrogen propulsion that represent a significant departure from the current technology. The disruptive changes ahead of us cannot be solved with today's process of isolated tools and teams. It will require much tighter integration between flight physics, aircraft structural design and analysis and testing teams. Using Simcenter™ software, which is part of the Siemens Xcelerator portfolio, the comprehensive and integrated portfolio of software, hardware and services, enables a concurrent way of designing, analyzing and testing an aircraft to achieve full traceability.

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Introduction

Today's aircraft are 75 percent more fuel and carbon dioxide (CO_2) efficient than aircraft from the early jet age. Yet, the growth rates currently forecasted and the historical rate of technological improvements are projected to lead to aviation's global CO_2 emissions tripling by 2050. If all other sectors achieve the emission reduction targets envisaged, aviation will constitute the majority of humankind's carbon budget by mid-century.[1]

Current kerosene-powered turboprops and turbofan aircraft have been optimized to near perfection over decades and provide a reliable and power-dense source of propulsion. Further incremental improvements, such as high-aspect ratio wings or larger engines, which could improve fuel economy further, are starting to face negative tradeoffs when considered at the full aircraft level.

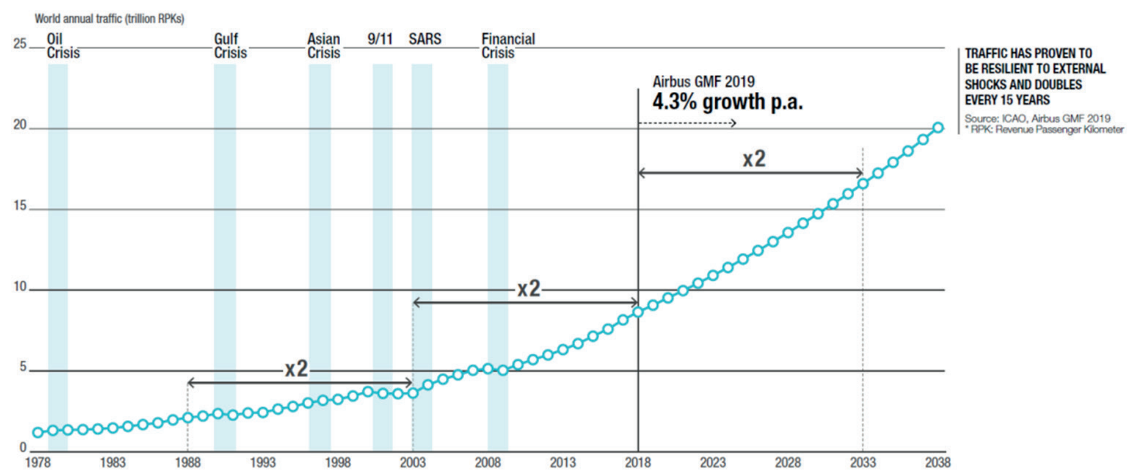

Figure 1. World annual traffic forecast. (Image courtesy of Clean Aviation Joint Undertaking)

Challenges in the aviation industry

Disruptive change is necessary. But moving from the entirely fossil-based fuel-powered system to the future aviation system with multiple energy carriers and architectures requires an exceptional research and development (R&D) effort to reduce energy consumption while ensuring safety and competitiveness. This transformation will take place in a dynamically changing global aviation regulatory framework that will create the conditions for such a transition.

Recent advances in electric battery technology and electric motors have already facilitated the design of electric vertical take-off and landing (eVTOL) aircraft with distributed electric propulsion (DEP) architectures, raising expectations that a pervasive market of more affordable air taxi services is achievable. Some eVTOL prototypes have had successful test flights and trials. However, significant work is still necessary, especially on battery performance and weight optimization to enhance the practical capabilities of eVTOL aircraft for society. As with commercial aviation, these advanced air mobility companies will need to work with the civil aviation authorities against a changing global aviation regulatory framework to adhere to safety standards and achieve certification.[2]

These new designs based on electric propulsion technologies have also resulted in nontraditional aircraft structures that require new approaches to aero-structural engineering and airworthiness. Traditional aircraft structures have followed semi-monocoque designs with various wing configurations that have had strength and stiffness criteria.

Currently, most eVTOL designs follow three different architectures: multicopter with multiple rotors in various configurations, a more basic form of a multicopter as a quadcopter with four identical rotors and fixed-wing configurations. Each of these designs has relative merits for their distinct mission profiles but all present new designs that do not fit into the traditional certification process.

Meanwhile, developing new or derivative aircraft within budget, on schedule and compliant with regulations remains a challenge for any manufacturer. Programs are experiencing delays of up to five years, costing manufacturers additional engineering hours and hundreds of millions of dollars in budget overruns.

In parallel, geopolitical tensions are driving investments to increase the capabilities of major defense platforms, including drones and fighters. Despite the spending increase, a sense of uncertainty pervades. New competition, increased digitalization and accelerated procurement timelines will continue to weigh on incumbent players as governments seek to get promising technologies to the field faster.[3]

In response to these challenges, there is a need for a systematic change in how aircraft are developed and certified, making use of new means of proof and processes available from digitalization. Digital solutions can contribute significantly by reducing development costs and validation phases while maintaining or increasing safety. New digitalization platforms also allow re-using digital data from one process to another, connecting digital skill tools that used to be siloed. Ensuring full traceability and continuity of all shared information makes the overall product development faster.

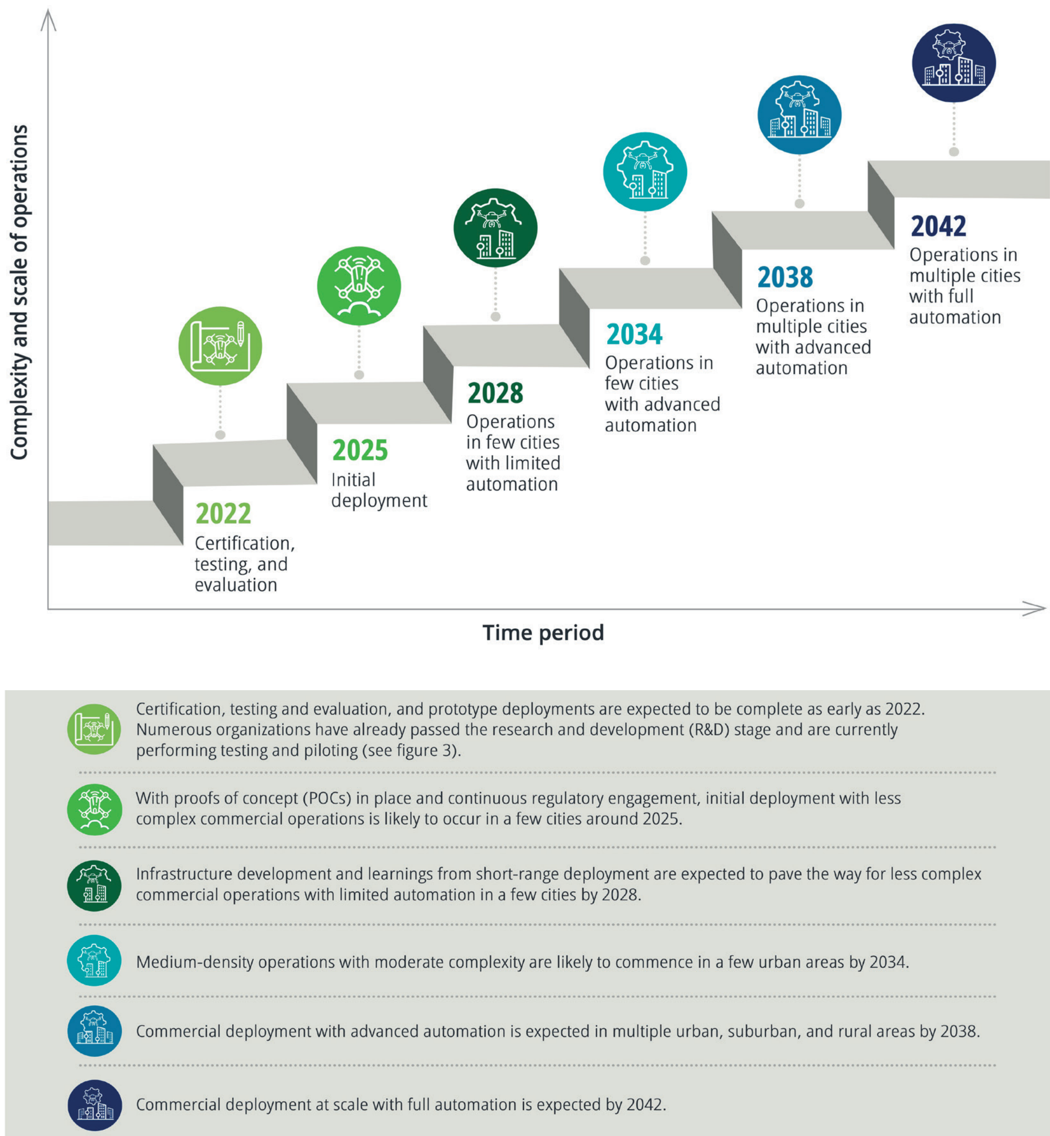

Figure 2. Operationalizing advanced air mobility. (Image courtesy of Advanced Air Mobility, Aijaz Hussain and David Silver)

Airframe development program

A typical airframe development process starts with defining the customer requirements and the mission. Engineers will consider different airframe architectures with specific systems and payload distributions to meet program needs. External loads due to flight maneuvers, gust and turbulence, landing and taxi and heating are estimated with experience or calculated rationally.

These external loads, combined with initial information on the aircraft structural architecture (wing ribs and spars, fuselage frames and stringers, engine pylons, etc.), are then used to estimate the internal loads that are carrying structures.

Conceptual design

During the conceptual design phase, the flight physics and structural design and analysis teams will perform several tradeoff studies to settle on the final structural architecture and design. At this stage in the program, the internal representation of the structure is kept coarse; internal loads are extracted and fed to analytical models to capture the margins of safety (also known as reserve factor) for failure modes like panel buckling or stiffener crippling.

As the program progresses, the number of loads considered to size the structure will expand to above 10,000. This puts pressure on the flight physics team to deliver as this is the starting point for a correct initial structural sizing process.

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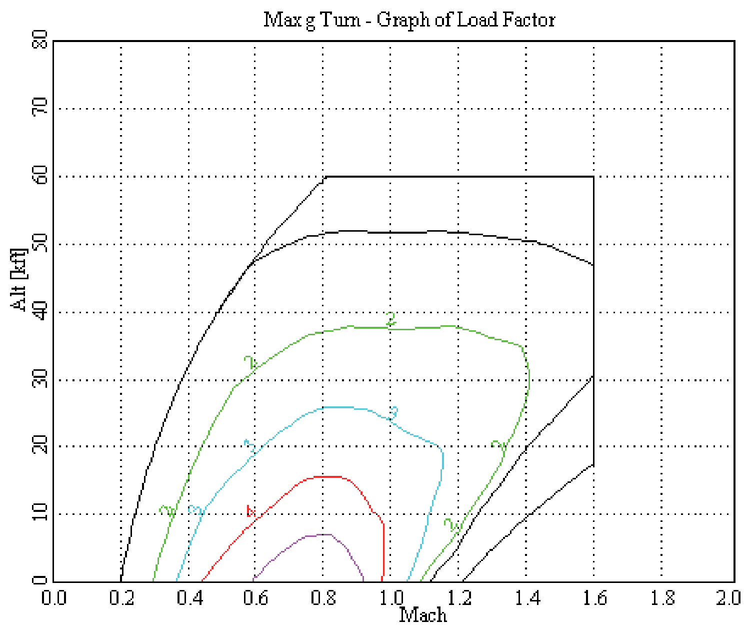

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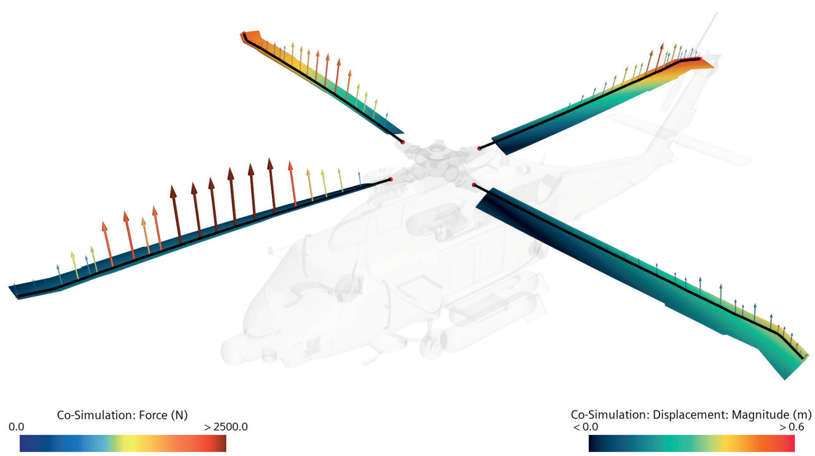

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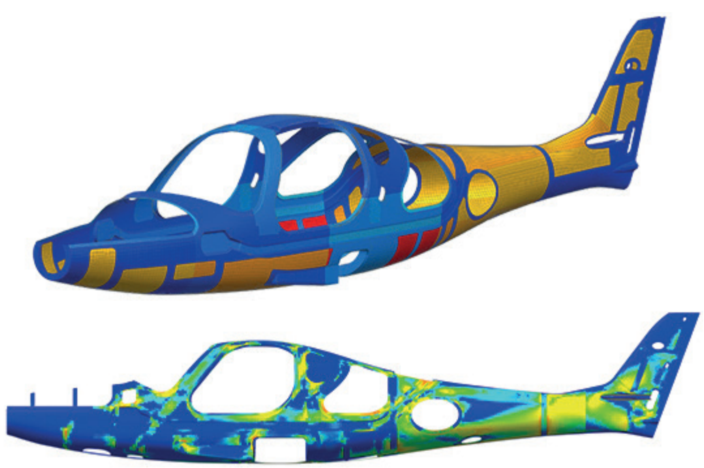

Figure 3. From top to bottom, a typical mission envelope, helicopter blade loading and a global FEM model.

Product engineering

As the design matures, engineers will add structural details like stacking sequences for composites or web and flange height and thicknesses for metallic stringers. Then they will define critical load cases for the wing, horizontal tailplanes and vertical tailplanes to optimize each structure against a subset of loadings. At this point, it will also be necessary to represent certain parts in more detail for fatigue and damage tolerance calculations.

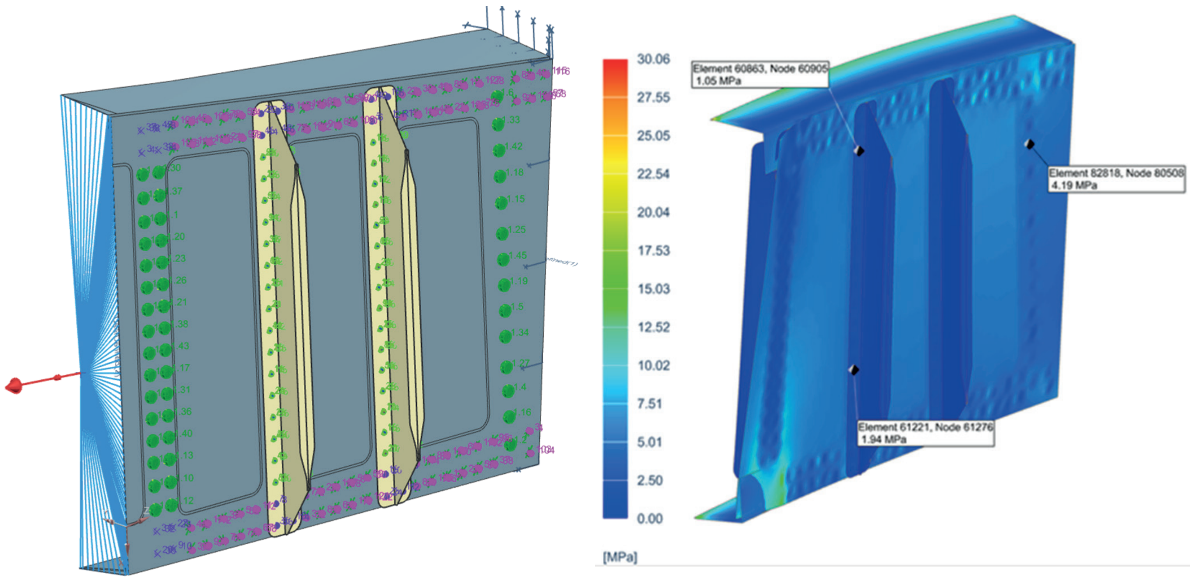

Figure 4. Detailed geometry and simulation model.

Verification and certification

As part of the certification effort, the airframer needs to show that the aircraft conforms to all requirements by conducting a thorough verification process. In the structural analysis context, the airframer must use simulation, test or other means to substantiate the design is compliant with all strength, deformation, fatigue, vibration and aeroelastic stability requirements. This often results in an exhaustive list of design modifications that must be run through all the load cases to reserve the calculation process, putting the program at risk of delay.

For decades, airframers have organized this workflow in a set of silos, with flight physics, design and stress teams, each having its dedicated tools and workflows. Time is lost deriving the required critical load set for a substructure, converting the design into a finite element analysis (FEA) model, extracting all of the information for a reserve factor calculation and organizing the reporting over different tools. Ensuring the coherence of design concepts, simulation models and test objects was tedious, and the risk of costly human error was imminent. The process worked well for incremental evolutions of well-known architectures but has not been adapted to take us through the disruptive change ahead.

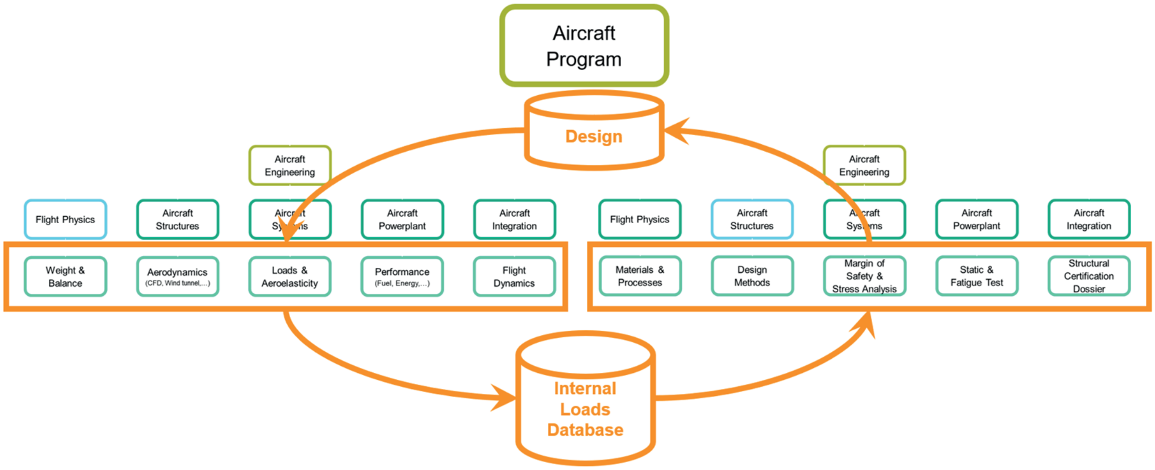

Figure 5. Iterations between flight physics and aircraft structural design.

Impact on the airframe design and analysis workflow

Based on the previously described challenges, engineers will need to design future airframes to integrate innovative technologies such as hybrid-electric and hydrogen propulsion systems. They will need to explore new configurations and performance ranges that have not yet been achieved in aviation:

1. Multiple propellers may be installed with an effect on aerodynamics, vibrations, loads, strength and fatigue.
2. Hybrid-electric propulsion systems with constant mass battery packs will impose new constraints on the airframe.
3. The fluid properties of liquid hydrogen are completely different from kerosene, requiring a step change to larger, more voluminous fuselages to integrate the cylindrical tanks. A radically different configuration, like the blended wing, could be the most attractive arrangement.
4. Further reductions in drag and weight will remain essential to assure the viability of any future aircraft program.
5. Unmanned air systems will modify and extend the flight envelope beyond human limitations.

Figure 6. AMPERE - a regional distributed electric propulsion demo aircraft. (Image courtesy of ONERA)

Enabling these new configurations will require advanced capabilities to predict design parameters and performance at the aircraft level and sharing these with the partners and certification authorities. A virtual airframe design, integration, verification and validation platform is needed to scale and correlate flight and ground testing by leveraging simulation. Innovative concepts like active flutter control and optimized load distribution on high-aspect-ratio dry wings, together with new materials and manufacturing concepts will significantly reduce fuel consumption while requiring new certifiable methods and adapted means of compliance.

A connected airframe structural design and analysis approach

To address these disruptive changes, aircraft manufacturers need to move from today's process of isolated tools and teams to much tighter integration between flight physics, structural design and analysis and testing teams. More specifically, improvements in the following areas are essential:

- Concurrently creating airframe structural designs and analysis models
- More efficient and traceable loads to reserve factor calculation process
- Closer collaboration between simulation and test teams
- An agile stress method creation and utilization toolbox

Creating and verifying new airframe configurations will require extensive multidisciplinary optimization capabilities to predict the best design parameters and associated performance at the aircraft level. The computer-aided design (CAD) model should be crafted to support the efficient generation of many assembly or subassembly variants and their consumption for computational fluid dynamics (CFD), aero-elastic, structural and stress verification analysis, considering innovative manufacturing concepts as well.

Innovative concepts like freely flapping wingtips on high-aspect-ratio aircraft or integrating cryogenic hydrogen systems create more challenging and dynamic load cases with emphasis on thermal and nonlinear effects. The ability to efficiently calculate and query through this vast amount of information and filter and combine them in a traceable way for further reserve factor analysis on the subassembly level will be paramount.

Over the next decade, aircraft will take to the air with configurations and performance ranges that have not been seen in aviation. Although digital solutions can contribute significantly to keeping the development costs of these new programs under control, verifying the static and dynamic global finite element method (FEM) models with tests will still be required. It is possible to further save time and reduce risk by using design and simulation data to prepare the test so that all relevant phenomena are captured, facilitating the downstream simulation model updating.[4]

It has been a standard practice in the airframe industry to combine coarse global aircraft FEM models for load path analysis with analytical stress methods for initial panel or fastener sizing to speed up load iteration loops. These calculations were developed with the assumption they will not necessarily hold for future structural configurations. A dedicated application is required to create and validate innovative stress methods that open the design space beyond classic conventions.

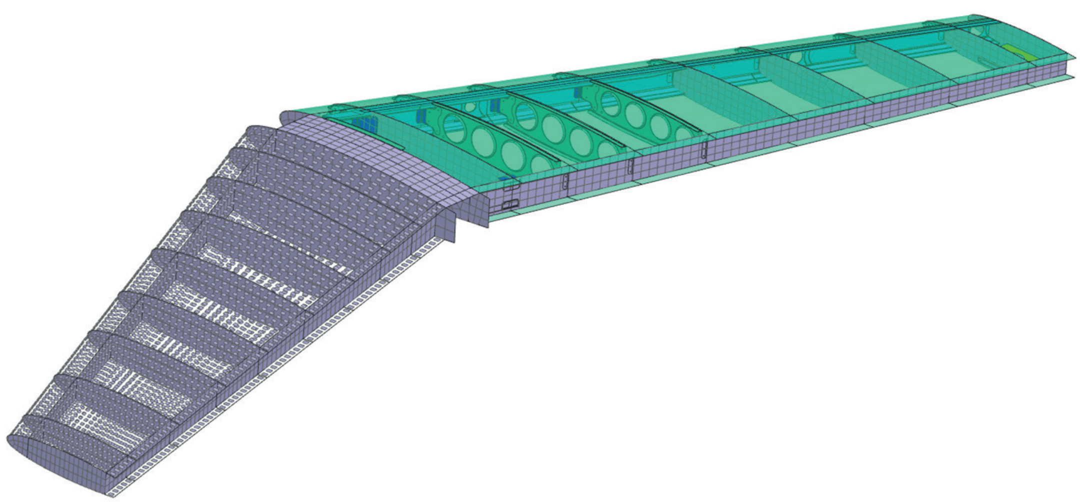

Figure 7. Integrated CAD and FEM of aircraft horizontal stabilizer (tail).

How Siemens can help

Siemens Digital Industries Software has developed dedicated solutions that significantly speed up the airframe design and analysis process. Using Simcenter helps engineers concurrently create structural design and FEA models for load path calculations or local for fatigue and damage tolerance analysis. Using Simcenter also helps you create and use analytical stress calculations that consume information associatively from design, FEA or material databases.

Any change can be propagated automatically through the engineering workflow, simplifying the setup of multidisciplinary optimization (MDO) analysis. You can benefit from full traceability between the design, selected material and the method, inertia and loads used to size the structure. You can accurately predict flight maneuvers, landing, gusts and heat loading cases, combined, down selected and passed on to the stress analysis group for an accelerated maturation of the structural concept.

You can use Simcenter to create global FEA models to capture the structural dynamic behavior of the aircraft as well as prepare and execute ground vibration tests to validate these models. This ensures consistency between the simulation model and the test objects, accelerating the updating process later and reducing the risk of missed information due to poor instrumentation. You can use the updated model for flutter simulations, reducing the time to clear the envelope for the first flight.

You can also use Simcenter to verify innovative stress methods more effectively with virtual coupon testing and adaptive multiscale modeling to assess their performance in more complex designs, both for metallic and composites. This allows for partial digitalization of the pyramid of tests to validate new materials, reducing cost and accelerating verification.

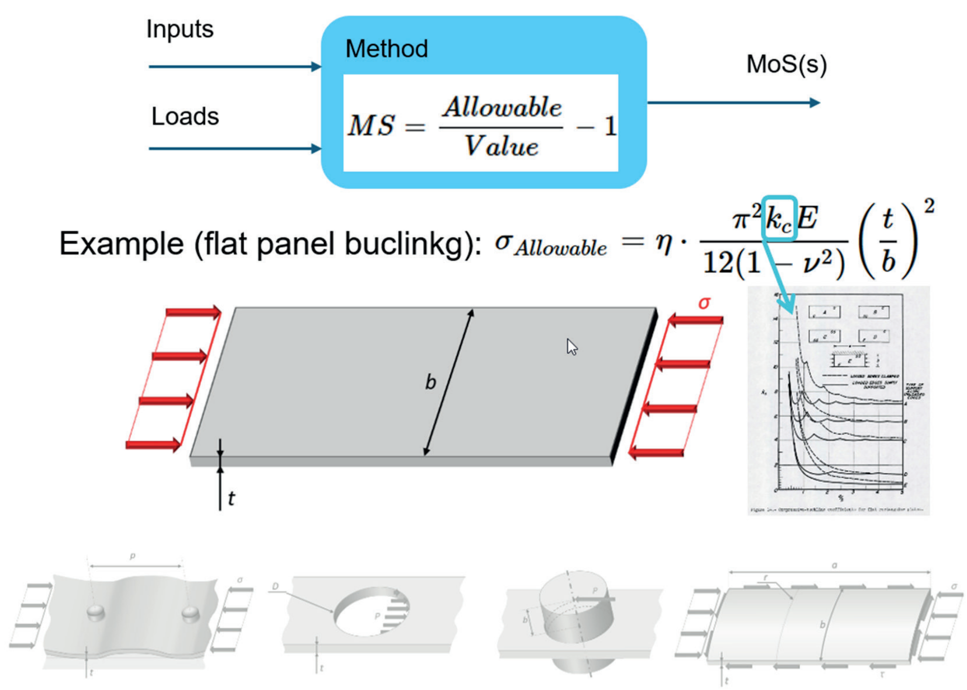

Figure 8. Stress methods applied to a global FEM.

Conclusion

Achieving the massive shift to climate-neutral aviation will require a radical redesign of the current aircraft structural architecture to accommodate all the new propulsion innovations that will be developed to enable this shift. To remain competitive and meet the industry deadlines, manufacturers will need to reengineer the aircraft development tools and processes from isolated, disconnected tools to a tight integration across all disciplines providing greater efficiency, accuracy and traceability throughout the engineering process from requirements to certification.

Using Siemens Xcelerator provides you with this environment across the product design and engineering, model-based systems engineering (MBSE) and verification management digital threads. You can use Simcenter to not only size and optimize the detailed design, but the solutions also provide you with the elements for proof of compliance based on virtual and physical test data. This effectively contributes to aircraft program execution excellence by enabling you to stay on time and within budget.

References

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