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# Analysis and simulation in aircraft structure certification

How digital tools offer a simpler path to  
airworthiness certification

## Executive summary

The certification of an entire aircraft structure is extremely complex. There are different aspects an applicant for structural approval must consider to prove that the strength of that structure sufficiently meets the design goals of the entire system.

Organizations using simulation and analysis tools effectively see the benefits in their ability to achieve certification faster and with drastically less total cost than those who do not maximize these tools.

# Aircraft structure design considerations

All aspects of the structural certification are subject to the Federal Aviation Administration (FAA) regulations that specify the requirements of the structure depending on the type of aircraft. Engineers must adhere to these requirements by looking at every possible condition and operating environment that the aircraft could possibly operate under, and demonstrate by analysis or test that each production copy will perform as intended and without any structural failure.

## Requirements and criteria begin in preliminary design

Fundamental analysis begins very early in the stages of conceptual design. The structure necessary to support the entire aircraft depends on the design mission of the aircraft in question. How high and fast will this aircraft need to fly? What is the payload, people or cargo, and how much payload will it need to carry? How far will it need to fly to deliver that payload? These are the fundamental design criteria affecting the type and size of aircraft an airframe manufacturer must address as early as possible.

After determining the type and size of aircraft, the manufacturer typically designs the outer aerodynamic shape, which includes the basic airfoil shape that will meet the mission, the planform area of the wing, the volume and

shape of the fuselage, and the airfoils and size of the tail of the plane.

## Loads and static strength

The next large-scale general step in substantiating the structure takes the aerodynamic general arrangement definition of the new airplane. Conducting a comprehensive analysis evaluates what aerodynamic loads are applied to the aircraft at all the various points of the airspeed or flight envelope.

Figure 1 shows an example of a flight envelope for a propeller-driven plane. The load factor ( $n$ ) is calculated based upon the various design airspeeds for the particular aircraft. The various speeds listed are:

- $V_s$  = stall speed
- $V_a$  = maneuver speed – this is the highest speed at which the maximum deflection of the controls can be applied
- $V_c$  = cruise speed
- $V_d$  = dive speed

These speeds are inputted into a loads analysis, which evaluates the maximum loads and the associated aircraft condition and configurations.

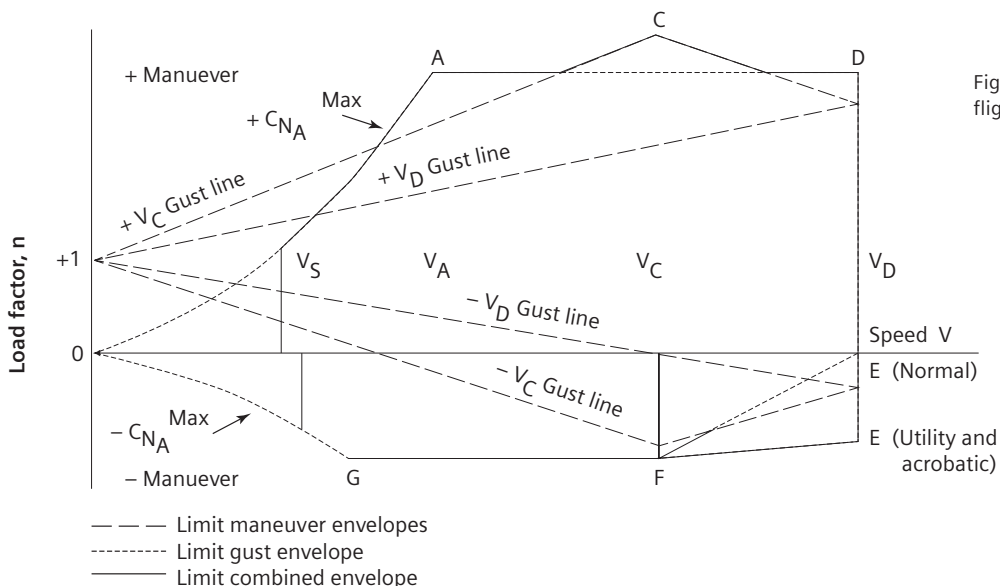


Figure 1. Example of an aircraft flight envelope

What engineers must do is analyze and find the biggest, worst-case forces that will shear, twist and bend (up, down, forward, and rearward) all the various parts of the structure. They must investigate what the loads are at all the various aircraft weights, centers of gravity, and at high and low speeds. At each of these points on the envelope the engineers must determine the loads associated with certain aspects, such as gear up/down, flaps up/down, and every possible combination of the configurations.

The critical design loads and the critical conditions are the highest load for each and every combination of points on the envelope and each condition. There are literally hundreds of combinations of points and configurations on the flight envelope to evaluate and investigate.

For example, consider the critical condition for wing spanwise bending. Imagine pulling straight up on the tips of the wings and holding fixed where the wing attaches to the fuselage; this is at a heavy weight in the cabin

when there is little fuel in the wings and the aircraft is at the maximum prescribed gust load. At this point, the wing is lifting up, and the gust is pushing the aircraft down so the wing bending is the highest in this condition.

From there, analysis of the actual physical structure ensures that the static strength is sufficient in every possible operating point the aircraft could see in service. These critical loads are called the “design limit” loads.

In general, the FAA requires static testing of the structure and applying a minimum load of 1.5 times the design limit load (the ultimate load). While the structure may flex, it can show no failure, not even a crack, or any evidence of permanent deformation; this would indicate the structure entered a critical area in its material property limits. While all of this is happening, there are ongoing detail design changes to the physical structure. Robust and disciplined configuration management is absolutely critical at this stage.

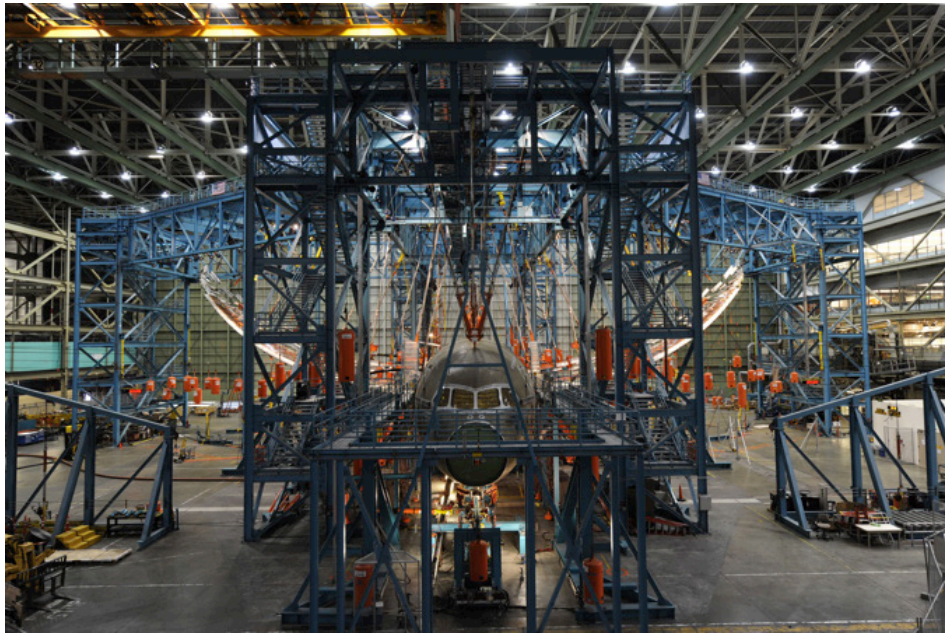


Figure 2. Positive static wing bending test of Boeing 787, Wired Magazine online, March 2010.

### Fatigue and aeroelastic considerations

As important as static strength is to the overall reliability and safety of the aircraft, it is not the only structural consideration. Engineers must also design the airframe structure to meet the physical rigors and long-term effects of repeated flexing of the structure, or fatigue strength. The structure flexes in flight when under changing aerodynamic loads so evaluation for structural stability in these dynamic conditions is necessary. These investigations are the fatigue and flutter substantiations and involve just as much rigorous analysis and test as the static test program.

### Aircraft fatigue analysis

If you've ever bent a paper clip back and forth until it breaks, you've performed a fatigue failure analysis. Bending a paperclip will permanently deform it and harden the metal locally, rendering it less "plastic." Fatigue failure is bending the paperclip back and forth repeatedly, increasing its internal hardness until it cracks and breaks.

In normal operation, wings flexing up and down over time is analogous to the paperclip. If the design of the airplane is right, the wing will be in the linear part of its composite stress/strain curve when applying a repeating bending force up to and including the design and ultimate limits (figure 3). The structure will flex and return to its shape but won't permanently deform.

Even within this linear range of the stress/strain curve, with enough cycles, any material can succumb to fatigue failure. The guidelines engineers use to determine the long-term effects of this repeated flexing are called S-N diagrams (figure 4).

The engineers must ensure that the number of cycles the aircraft is expected to see in service, as estimated by empirical data with some level of factor of safety assumed, never gets close to the fatigue failure limit of the various parts of the structure.

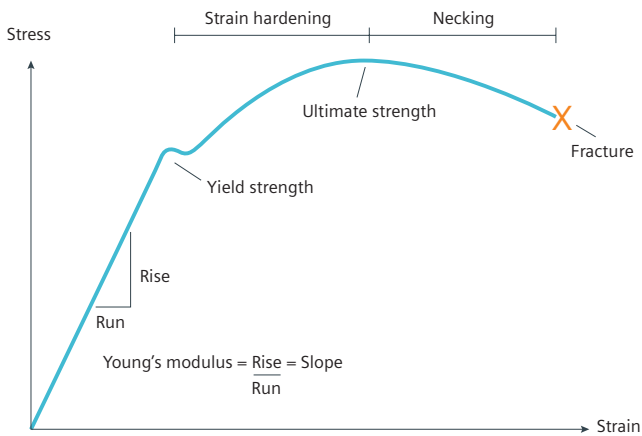


Figure 3. Example of stress/strain curve for low-carbon steel. The stress is a force applied to the material (tension in this example). The strain is the stretching or "elongating" of the material. When the stress is higher than the yield strength, the material permanently deforms, hardens and ultimately breaks. Under less stress than the yield strength, the material will return to its original length/shape. The wing's actual physical structure has a composite stress/strain diagram similar to an individual material curve.

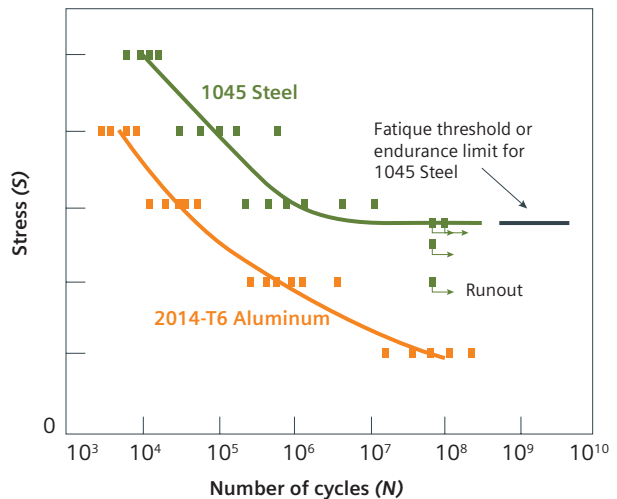


Figure 4. S-N diagram for a type of aluminum and steel. Note that where the material curve is horizontal goes horizontal with a large number of cycles, it indicates that no life limit is necessary. The material is "elastic" enough that it will not fail in fatigue regardless of the number of cycles.



### Flutter evaluation

An additional impact of a flexing structure and a structure that is designed to be in motion deals with both the dynamic and aeroelastic effects of that movement and flexing.

Every physical article has some natural harmonic frequency that it tends to vibrate. The simple example is a ruler where the first inch or two is on a table edge and the other end extends into free space. If the free end is bent up or down and released from a bent position, the ruler bounces like a diving board. The initial frequency of that vibration is the natural harmonic for that material and shape. Friction naturally dampens the vibration until it comes to rest. Introducing an external pulse at the same natural harmonic frequency causes the ruler to keep vibrating until that pulse was removed.

Upsets in nature in the atmosphere like wind gusts and turbulence are just like introducing an input vibration into the free end of the ruler; the flexing and resulting vibration of the wing is just like the ruler clamped to the end of the table.

The vehicle needs to be evaluated with respect to this movement by introducing and evaluating varying frequencies of vibrations to ensure that at no time will a harmonic mode lead to flutter, especially one where the amplitude (deflection of the structure) gets larger and larger. The result could be catastrophic in the case of a divergent flutter mode where the structure can literally be torn apart from the resulting vibration.

### The role and importance of simulation, analysis and test

There will always be a need for physical testing. However, virtual simulation analysis can supply sufficient results, reducing the need for a test to satisfy a required means of compliance. The inherent value of performing the simulation studies is to predict the behavior of the system without investing time, money, and effort into producing iterations of test articles for physical testing.

Aerostructure sizing requires computing thousands of structural analyses that feed into aircraft airworthiness certification. A lack of consistency in getting the right data for stress analysis and using the right engineering methods, sharing work and publishing stress reports makes the aircraft certification process difficult and long. Automating and standardizing the process are key challenges for airframe structural analysis. Maintaining visibility and traceability of specific data, models, processes and methods from concept to end product is a constant struggle.

The global simulation process means many engineering teams work closely together. Automating the process accelerates and improves the efficiency of design-simulation iterations.

By using end-to-end processes for aerostructures that take advantage of simulation throughout the product lifecycle, manufacturers have found they can deliver innovative products on time and with predictable performance.

From the perspective of owner-operators, this will also impact how quickly and accurately the analysis work can be completed as part of continuing airworthiness. These processes have enabled them to reduce model preparation time, shorten design-analysis iterations, evaluate tradeoffs across multiple disciplines, streamline development for on-time delivery and improve the quality of designs. Process standardization helps tackle this problem by improving process consistency and limiting the risk of errors that reduce availability and readiness.

The pervasive industry need is a comprehensive collection of simulation plus advanced test methods, and data management tools that streamline the global simulation process from facilitating CAD geometry definitions to providing a CAE environment.

A digital certification platform, comprised of an integrated system that encompasses the many analyses and reports required for readiness certification in a transparent environment, maximizes traceability and knowledge capture. The platform includes:

- Automated integration of loads and geometry to construct assembly finite element stress simulations
- Integrated capabilities that calculate margin of safety
- Seamless report generation associated with system requirements via the product lifetime management system

# Conclusion

A complete aerostructure simulation solution enables traceable data and results while maintaining consistent global process control. In addition to a detailed finite element model (FEM) approach, end users can size aerostructure components using a library of analytical engineering methods. With the capability of generating stress reports with data and results of the simulation, end users benefit from a consistent and integrated global process, resulting in increased accuracy, time and cost savings and increased availability over the product lifecycle.

Integrating a simulation environment covering the full simulation chain can mitigate automation and standardization challenges in airframe structure analysis for airworthiness certification. This comprehensive digital twin would encompass the capture and traceability of customer requirements, data, knowledge and processes.



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