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Aircraft structural design in the future

NLR – Royal Netherlands Aerospace Centre

Climate change and the limited amount of resources on this planet necessitate a circular economy and a continuous decrease in environmental footprint. Reducing the structural weight of an aircraft is still one of the ways to decrease the environmental footprint. However, an aircraft structure experiences many load cycles and occasionally a high load during its service life as a result of ground operations, turbulence and manoeuvres. Reducing weight usually leads to higher stresses in the material and care must be taken that structural integrity is maintained throughout the entire service life of the aircraft. In this respect the designer must not only account for failure under high static load conditions (limit loads) that occasionally may occur, but also for fatigue under the many smaller load cycles that the aircraft will experience in service.

There are several empirical equations that describe the relationship between the nucleation and growth of fatigue cracks and the stresses experienced by the aircraft structural materials, but these equations are not derived from first principles and hence lack a physical basis. As a result, our understanding and current predictive capabilities of fatigue crack growth and life time analysis are limited, especially for variable amplitude fatigue. This inevitably leads to conservatism in the design, the necessity to perform full scale fatigue tests and, occasionally, unexpected fatigue crack findings and early need of repair. Many verified methods in the design approach have been developed by the fast expanding aerospace industry during the 1960's and 1970's. At that time, great developments in engineering were achieved with limited aid of computer calculations, simulations and data storage. Nowadays, the limitations in computer power and data storage are nearly gone and computer simulations are used in many aspects of the aircraft design approach. Yet, fatigue is not integrated in the overall design optimization approach and is usually considered at the end of the design approach with the available legacy methods. This results in a high level of conservatism, which has a large impact on the weight of the aircraft.

To incorporate aspects such as integrated design, manufacturability, inspectability, reparability, recyclability or re-use and to further decrease the structural weight of the aircraft, while maintaining structural integrity and the highest level of safety, we see the need for a clean-sheet holistic structural design and integrity approach. This white paper highlights our view on potential developments and implementation of materials, technology and methods that are necessary to achieve this goal.

The sky is the limit

In the distant future, when the sky is the limit, the design of an aircraft could be such that design rules and boundary conditions are implemented in one overarching optimization algorithm that runs on a quantum computer. The algorithm gradually improves the design by creating millions of virtual designs and evaluating results of virtual flight tests on each design. At the end the algorithm returns the perfect aircraft design with respect to performance, passenger comfort, aircraft noise, costs of manufacturing, cost of ownership, environmental footprint, etc, for a given mission profile or a range of possible mission profiles.
Such a process can be compared to millions of years of evolution in nature leading to an optimal bird design for a given mission profile. For example, the wings of an albatross evolved by small mutations and survival of the fittest into long and slender wings for minimizing drag, the wings for a bird of prey evolved to low aspect ratio wings for hovering over one location, wings of swallows are optimized for manoeuvrability at the expense of taking off from the ground and the wings of some owls are optimized for silent approach.

Once the optimum aircraft design is manufactured and taken into service, it is expected that sensors will monitor the loads and health of the aircraft. The information from these sensors feeds directly into a digital twin, where the information is enhanced with data from other sources (e.g. maintenance databases) and degradation models in such a way that it represents a digital copy of the physical state of the aircraft. The digital twin is continuously compared with the original design and maintenance or repairs are performed only when necessary.

Again an analogy with nature can be made, where the sensors and digital twin can be compared to the nervous system and brain of birds. The nervous system of a bird acts as sensors that monitor its flight loads and health; their brain alters their course when the forces on their wings become too large or they can heal themselves when they are injured.

One objective of the virtual flight tests in the optimization algorithm would be to determine the fatigue damage and static strength at every location during the entire service life based on the structural design, the intended mission profile and dynamic response of the design. Although the above described optimization algorithm and a complete digital twin are far beyond our reach in the short term, there are steps that can already be taken for the structural integrity aspects. Those steps address a variety of topics, such as material models, calculation and analysis methods, fatigue design philosophies, manufacturing technologies and structural health monitoring systems.

A bird-like conceptual airliner design by Airbus. The design is partly based on biomimicry and the goal of the design is to motivate the next generation of aeronautical engineers
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The next steps for structural integrity...

New fatigue design philosophy

A step with much impact would be the introduction of a new fatigue design philosophy in the structural design approach. After safety-by-retirement (safe-life), fail-safe and damage tolerance fatigue design philosophies, the next step should be a new fatigue design philosophy that is inspired by the laws of nature and should allow for more efficient structures that save weight, thereby reducing fuel consumption and CO_2 emission while maintaining the current level of safety. We would title the new philosophy as the **green** fatigue design philosophy and it should be incorporated in the holistic structural design and integrity approach. As a result, the multi-level optimization of the aircraft structural design is not only based on static strength (A- and B-allowables) [1-3], but especially on time dependent degradation mechanisms such as corrosion and the nucleation and growth of fatigue cracks.

The green fatigue design philosophy should acknowledge the initial discontinuity state distribution and the possible presence of rogue flaws through an appropriate rogue flaw distribution. The current damage tolerance fatigue design philosophy usually considers the initial presence of a conservatively sized crack (typically 1.27 mm) at a critical location. However, most aircraft manufacturers use a strict quality assurance system for material, parts and training and have high quality assembly facilities, such as automated drilling, etc. This decreases the chance of having large initial defects or rogue flaws in structural parts and components. The current deterministic damage tolerance approach does not give any credit for the high quality standards that are used. Additionally, long crack growth data does not show a significant influence of yield stress on the fatigue crack growth rate [4], but the yield stress does have a positive influence on crack nucleation and small crack growth at low stress intensity factor ranges and a negative influence on fracture toughness. Since crack nucleation and small crack growth are typically not considered in the current damage tolerance fatigue design philosophy, a proper trade-off cannot be made between the benefit of a higher yield stress on the fatigue life of the majority of the structure that contains no rogue flaws and the impact of the higher yield stress on the reduction of fracture toughness. A single probabilistic fatigue life assessment methodology with proper distributions for the initial discontinuity state and the rogue flaws should allow to make that trade-off. Non-destructive inspections (NDI) or other structural health monitoring (SHM) technology can then ensure that these rogue flaws do not grow to critical sizes and information from inspections or SHM sensors are used to update the initial discontinuity state and rogue flaw distribution through, for example, Bayesian statistics [5].

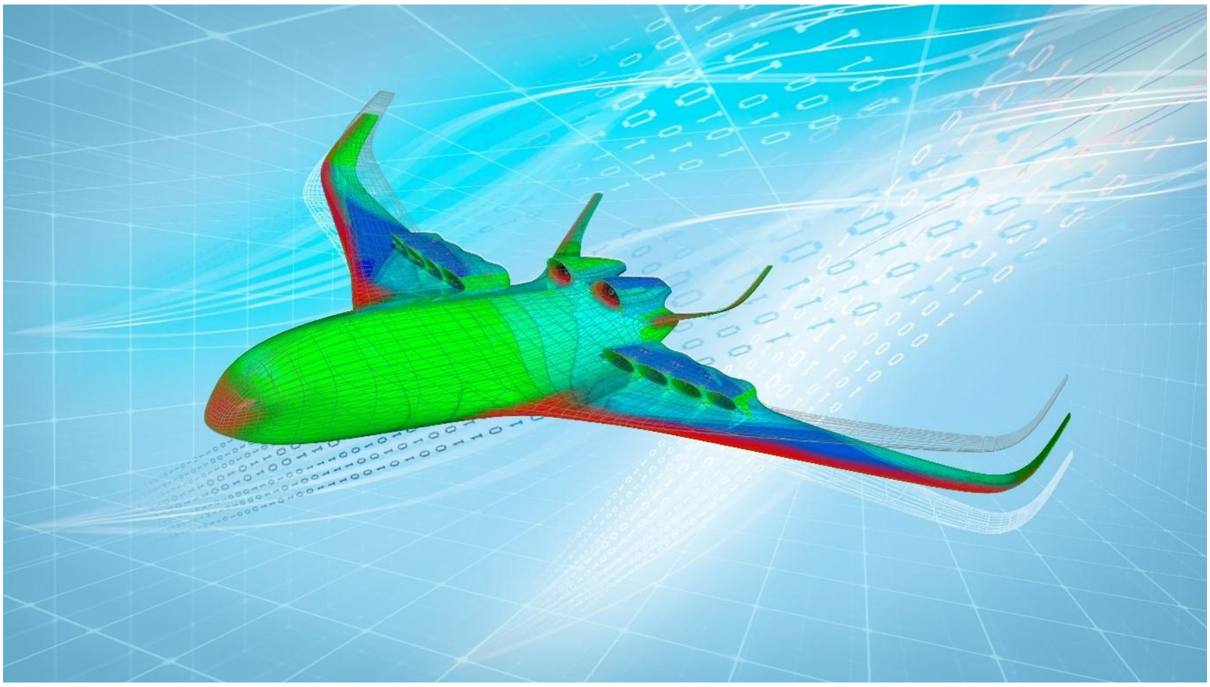
The stochastic nature of fatigue should be dealt with in a fully probabilistic structural risk analysis (SRA), which is already mandatory for military aircraft as described in MIL-STD-1530. In an SRA, all important scatter sources are taken into account in a probabilistic manner, including the variability in initial defect sizes, loads, material properties and the probability of detection of the selected NDI technique. In addition, environmental effects, loading frequency effects and load interaction effects for variable amplitude fatigue crack growth should be taken into account to arrive at more accurate crack growth predictions. Recently, the SRA was extended to multiple load path structures [6], because aircraft structures have multiple load paths where the remaining structure can carry the load without catastrophic failure after failure of a load path. SRA of single and multiple load path structures shows that there is significant conservatism in the current damage tolerance design methodology [6].

Virtual testing

Virtual testing of aircraft structures in monotonic loading up to failure, either quasi-static or at high strain rate, has evolved to a level where the predicted failure load is very similar to the failure load obtained during the actual test. Current airworthiness regulations require the failure load in quasi-static loading to be 1.5 times greater than the limit load, i.e. the load that should occur only once during the service life of the aircraft and for which no detrimental plastic deformation should occur within the structure. The origin of the 1.5 factor of safety (FoS) for aircraft structures dates back more than 80 years. Although proven safe, the historical basis for its value of 1.5 is unclear [7]. It could be based on variations in loads obtained from early flight tests or on the hardening behaviour of aluminium alloy with the idea that the ratio between failure and plastic deformation of the structure should be similar to that of the material from which it was made (at that time all metallic). Regardless of its exact value, the FoS should prevent failure of the structure in case larger than anticipated variations occur in external loads, local stress or material properties. However, since the introduction of the FoS enormous progress has been made in many areas, such as: materials and their deterioration over time; loads measurement, often unknown or highly uncertain at that time; aerodynamics and aero-elasticity nowadays yield much more accurate predictions; highly improved structural analyses, e.g. finite element methods, and computing power; production methods and process control, e.g. lower tolerances (less variability) and higher reproducibility; highly improved testing, e.g. much more realistic testing and much more test data acquired; and the existence of flight control systems that limit the maximum loads that a pilot can introduce. Since enormous progress has been made to reduce the uncertainty in these areas, a reduction of the factor of safety should be feasible, resulting in significantly lighter aircraft structures while maintaining the current level of safety. By means of a probabilistic approach, taking into account all important sources of uncertainty, the failure probability can be computed and the use of an assumed factor of safety can even be avoided altogether since it is implicitly incorporated in the probabilistic analysis [7]. In this way an optimal structure can be designed for a given probability of static failure. Application of a reduced factor of safety in the design will result in higher stresses and may introduce additional fatigue issues, also necessitating an improved fatigue design.

In addition to virtual testing in monotonic loading, virtual full-scale fatigue testing (FSFT) should be developed to assess the influence of manufacturing quality and tolerances on the stresses in the full scale assembled construction. A physics-based fatigue life assessment methodology that unifies crack nucleation, small crack growth and long crack growth is integrated in the virtual FSFT to determine the fatigue life distribution at each location of the structure. This requires a probabilistic variable amplitude fatigue calculation at every element of the full scale finite element model. A fatigue crack growth rate curve with multi-linear segments is expected to be the best option to unite the current fatigue life (S-N) and crack growth approaches into a single fatigue life assessment methodology [4,8]. This unified fatigue life assessment methodology should be able to give accurate failure distributions for the initial discontinuity state and rogue flaw distribution. In this respect it is noted that NLR has introduced a new, physics based, fatigue crack growth rate (FCGR) equation that automatically accounts for load interaction effects and bridges the gap between constant and variable amplitude fatigue [9].

The certification process should be adjusted to allow for a gradual shift towards virtual FSFT. An initial step in this direction is smarter testing and simulation, where the focus of certification slowly moves from physical testing to simulations or virtual testing at all stages of the test pyramid [10]. Initially the virtual FSFT should represent the physical FSFT that is at the top of the current test pyramid. However, in the future, the loads for virtual FSFT should not be limited to a simplified spectrum concentrated at the actuator locations of the physical test, but should be distributed loads from simulated flights over a period of the entire design life resulting in a more realistic fatigue spectrum. Accurate gust statistics with sufficiently small discretization combined with



Artist impression of a virtual flight test (© NLR 2021 – All rights reserved.)

validated loads models including aeroelastic effects should be used to simulate flights over a period of the entire design life [11-13]. This should result in an accurate load history from manufacturing and assembly to the end of the service life for every location in the aircraft. When environmental conditions such as temperature and humidity are also incorporated in the simulated flights of the virtual FSFT, the virtual FSFT becomes a virtual service life test. If degradation of material properties and the presence of fatigue damage are incorporated in a probabilistic manner, the virtual service life test also combines the probabilistic static virtual test with the probabilistic virtual FSFT, because limit loads for the static load cases are by definition obtained from the full scale load spectrum.

Therefore, the virtual service life test will give failure distributions or chance of failure of a given design for all different failure modes, e.g. static, fatigue, corrosion, creep, wear, etc.

Digital twin

Once the aircraft is taken into service, sensors will continuously monitor the loads and health of the aircraft. A digital thread is used to track the history of individual aircraft structures in terms of flight parameters, loads, environment, structural modifications and repairs, maintenance, etc. The digital thread together with the probabilistic failure mechanism models are used to calculate the current physical state of the structure, i.e. the digital twin. The digital thread, which includes continuous load monitoring, is used to determine the primary parameters that affect fatigue crack growth and the data is compared with the virtual service life test to determine when maintenance or inspections are needed. The digital twin and Bayesian updating enable predictive maintenance and an optimized inspection scheme, parts retirement scheme and SHM solutions.

Material developments

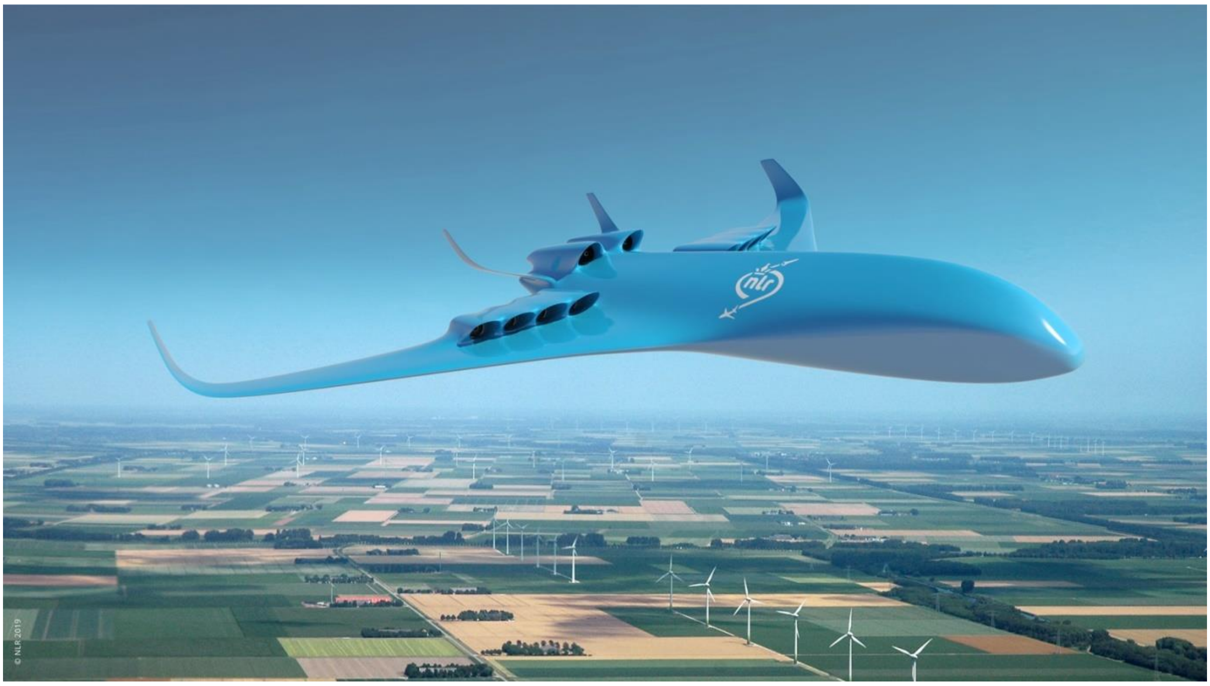
Additive manufacturing and other advanced manufacturing technologies provide more freedom in the design stage. This allows for shape optimization software to design structures that have a very efficient stiffness to weight ratio. However, currently there is no design approach that incorporates damage tolerance considerations to guarantee that a shape optimized structure or component is actually damage tolerant [14,15].

The increase in calculation power and atomistic modelling does not only enable the optimization of topology, but also of alloy composition and microstructure to obtain better strength and ductility with less or no use of critical materials. The direct crack length vs. cycles fitting methodology that has recently been developed [4] gives a multilinear FCGR curve, where each segment corresponds to a different crack growth micro-mechanism. With this methodology it is possible to exactly determine the effect of microstructural changes on specific segments of the FCGR curve, hence enabling to improve or tailor the damage tolerance capability of metallic alloys. Accurate fatigue modelling with a unified model for fatigue crack nucleation, small crack growth and long crack growth, together with FCGR data up to final failure will allow for optimized material selection in terms of weight, stiffness, fatigue, fracture toughness, cost, environmental impact, recycling or re-use.

Engineered residual stresses due to cold working processes or laser shock peening are only marginally incorporated in the current design approaches and no benefit in terms of increased inspection intervals is possible, because there is no quality assurance of the process or proof that all areas that should be treated have indeed been treated. Since manufacturing data is also stored in the digital thread, this allows to use the full potential of residual stress technology in increasing the damage tolerance performance of structures.

The use of fibre reinforced composite materials has increased gradually over the years and its application is now widely applied in primary structures such as wings and fuselages. It is expected that a holistic design approach will result in a hybrid structure, which comprises metallic alloys, fibre metal laminates and composite materials, and asserts the interaction between materials groups in terms of thermal response, corrosion and fatigue. The holistic structural design approach should fully exploit the potential of composite materials by using appropriate material models so that a "black aluminium" design is avoided. Using information from material property models, material and manufacturing costs, repairability, recycling, etc. for composite material should allow the holistic structural design approach to select the optimum material for each application and loading cases.
Incorporation of automated fibre placement technologies for composite materials and active fibre steering according to the "put the fibres where the loads are" principle should lead to lower structural weight [16,17]. Additional benefits for composite materials can arise from using the additive manufacturing aspect of these materials and make multi-functional designs e.g. by integration of systems like antennas [18]. Composite materials with a high performance thermoplastic matrix offer new design and assembly philosophies since thermoplastic materials can be welded and offer the potential of recyclability. Currently, in most cases thermoset matrix materials are being used and the design is driven by static damage tolerance requirements and dynamic no-growth principles. Due to the lack of accurate physical failure models and failure criteria, a semi-empirical design rule is used that limits the maximum allowable strain level at the ultimate load. This leads to conservative and hence not fully optimised structural designs. Better material, environmental degradation and failure models for composite material in general, and particularly for active fibre steering, together with using more damage tolerant thermoplastic materials or lay-ups [19,20] should allow the use of higher design stress/strain levels. In that case, fatigue of composite materials may become a design discriminating factor. Therefore, better fatigue models for composite materials have to be developed.

Self-healing of fatigue damage in metallic alloys has been investigated, but a successful method is still lacking. A better physical understanding of fatigue crack growth possibly results in a derivation of the fatigue crack growth rate equation from first principles [9] and this knowledge may offer ways to decrease or even invert fatigue damage in service. On the other hand, thermoplastic composites are very suitable materials for self-healing of fatigue damage and are probably the closest approximation to natural materials with a vascular system. When self-healing is combined with embedded fibre optic sensors that act as a nervous system to detect loads or impact damage and the digital twin acting as the brains, the whole aircraft structure becomes similar to that of a living organism: a true mechanical bird!



Artist impression of an alternative aircraft configuration that uses hybrid electric propulsion (© NLR 2019 – All rights reserved.)

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This white paper is a joint effort of the departments Flight Physics & Loads, Collaborative Engineering Systems, Structures Testing and Evaluation, Structures Technology and Gas Turbines & Structural Integrity within the Aerospace Vehicles division of NLR.

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