A Framework to Implement Probabilistic Fatigue Design of Safe-Life Components

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Within the aerospace sector, aircraft landing gear are classified as 'safe-life' components [1]. The 'safe-life' of a component represents the life (often defined in flight-hours or flight-cycles) at which the component must be retired from service. Component safe-life values are computed using 'classical' fatigue analysis methods, such as a stress-life approach incorporating Miner's Rule [1]. However, safe-life fatigue analysis contains many sources of variability within the design parameters of the analysis process, such as scatter in material properties and uncertainty in loading. This variability propagates through the analysis process into component safe-life values and is currently accounted for using conservatism and safety factors. The use of safety factors is known as a deterministic mindset or approach, whereby all design parameters are set to single and safe values. The introduction of conservatism into the analysis process could lead to components being 'over-sized', increasing component weight and life-cycle cost, thereby compromising the performance of the overall structure [2]. In addition, conservatism can also lead to the potential component safe-life not being fully exploited due to early retirement from service.

Probabilistic approaches to fatigue design and analysis enable the variability in design parameters to be statistically characterised using probability distributions (e.g. Normal, Weibull, etc.) [3]. The statistical characterisation of design parameters permits the variability to be propagated through to the output of the safe-life analysis process to produce a probability distribution of the accumulated fatigue damage or the component safe-life. The component reliability (or probability of failure) associated with the component safe-life can then be computed from the output probability distribution. As a result, probabilistic approaches enable a more accurate representation of the statistical nature of fatigue design parameters and have been successfully applied to the fatigue analysis of safe-life components in the Light Aircraft [3] and Rotorcraft sectors [4]. A probabilistic approach offers the opportunity to better represent and understand the variability within component safe-life values, increasing the confidence in the component retaining its structural integrity throughout its design life. This increased confidence has the potential to yield more efficient designs that remain safe in-service.

Current research work by the authors aims to develop a probabilistic approach for the fatigue design and analysis of safe-life aircraft landing gear components. This paper aims to document the authors' experience in the development of a probabilistic approach to date, as well as identifying on-going challenges and considerations for future implementation. This will be achieved by briefly introducing the methods required to support a probabilistic approach, along with discussing the 'mindset' that engineers will need to adopt to ensure the successful implementation of a probabilistic approach in the future.

Whilst probabilistic approaches offer opportunities to reduce the conservatism currently required in fatigue design, the additional technical knowledge that must be developed is significant. To capture the authors' experience in attaining this technical knowledge, this paper will provide an entry-level introduction into the core method types required for a probabilistic approach and the challenges of selecting such methods:

- Statistical Characterisation: *the selection and fitting of probability distributions to design data.*
- Probabilistic Fatigue Method: *the propagation of variability.*
- Surrogate Modelling: *the approximation of computationally-demanding processes.*
- Sensitivity Analysis: *the use of probabilistic results to identify design drivers.*

Beyond the additional implementation of new methods, the adoption of a probabilistic approach will also require practising engineers to adapt to a new mindset of accepting variability in design parameters and component safe-life values, compared to the deterministic mindset currently used. The paper will present how systematic processes can be used to increase the understanding and confidence in results from the statistical characterisation of design data, to support the transition to the probabilistic mindset. In addition, the change of mindset will also require the development of probabilistic design criteria, in the form of 'target reliabilities' and potential routes to defining such criteria will also be discussed.

The reluctance to employ probabilistic approaches is also often founded in the additional effort and resources required, compared to a deterministic approach, in terms of required data, computational resources and time to develop and learn methods [5]. Therefore, this paper will conclude by demonstrating how the methods required for the probabilistic design and analysis of safe-life components can support other design activities and developments in the aerospace sector, to increase the potential utility of probabilistic methods. As aerospace fatigue design is entering the age of 'big-data' [6], systematic and robust statistical characterisation methods are required to fully exploit the data being generated, especially from the in-service monitoring of aircraft. In addition, as optimisation becomes ever more deployed within aerospace structural design, the need for faster evaluations of finite-element programs can be supported through surrogate modelling. Likewise, the introduction of 'digital twins', whereby an often computationally expensive mathematical model of the in-service component is updated based upon in-service data in real-time [6], is likely to require surrogate modelling methods.

In summary, the development of a probabilistic approach would not only permit reduced conservatism within the fatigue design and analysis of safe-life components but will also support other rapidly developing areas of aerospace fatigue design. Figure 1 summarises the paper, providing an overview of how the different methods of a probabilistic approach can be combined to support the development of more efficient and optimised components. This paper presents work performed as part of the Aerospace Technology Institute funded "Large Landing Gear of the Future" project in collaboration with Safran Landing Systems.

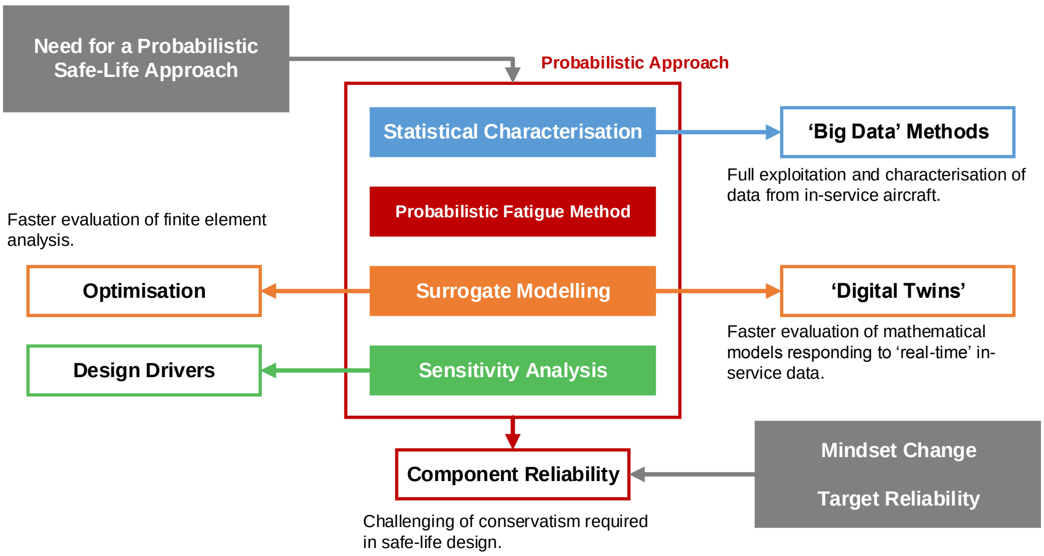

Figure 1: An overview of the methods required for performing probabilistic fatigue analysis and how they can be used to support other advances in aerospace fatigue design and analysis.

Keywords: Safe-life, Fatigue Design, Probabilistic Methods, Surrogate Modelling, Big-Data.

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