Complexity of Understanding the Failure of Aerospace Composite Structures

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Due to its multifaceted nature, failure analysis is a complex field of engineering. This is particularly the case with aerospace failure analysis, due to the introduction of new materials, which operate within complex conditions and often with a combination of extreme environmental factors. Aerospace components are subjected to fluctuating stresses, often operating in extreme and varied environments around the world. Traditionally, these components fail by modes of fatigue fracture, corrosion, brittle fracture, ductile overload, high-temperature corrosion, corrosion fatigue, creep wear, abrasion, and erosion. But what challenges face the contemporary and future aerospace failure analysis professionals when we add the complexities of composite material families into the mix?

Over the past decade, advanced engineering composites have become a mainstream family of materials in the aerospace sector, resulting in the significantly reduction of

weight of a range of aircraft structures. These advanced materials offer weight savings of 20% on average, compared to more conventional aluminum and metallic materials. New generations of commercial transport aircraft use composite materials extensively, with the structural elements of these new aircraft being similar to their metallic predecessors. Fiber reinforcement is added to resin systems to increase the tensile strength and stiffness of the finished component. The main types of fiber reinforcement used in the advanced composite industry include carbon, graphite, aramid, ceramic, glass fibers, and in the future carbon nanotubes.

Failure of composite systems is a complex multistage process, which is completely different to traditional metallic systems. The interesting thing to keep in mind is that the failure of a composite can be initiated in one mode, but the propagation and final failure modes can be significantly different. Composite materials display two main types of failure: (1) failure of unidirectional layers and (2) failure of unidirectional layer due to longitudinal tension. In a large number of cases, composite failure is initiated internally at the microlevel (fiber or matrix). But it is only once failure has propagated that changes in material behavior and appearance are observed. The failure of a composite manifests as a breaking of fibers, development of microcracks in matrix, debonding between fibers and matrix, and delamination, in which there is a separation of different laminated layers.

Therefore, before failure occurs at macroscale, the material response changes significantly at the microscale. This change in material response precedes component failure and stems from a large number of microfailures and subsequent nonlinear material behavior. For simple unidirectional laminates, the stress-strain behavior is typically linear. When an applied load exceeds a threshold, then the

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stress-strain response becomes increasingly nonlinear. However, when a unidirectional lamina is subjected to increasing tensile force in longitudinal tension, all fibers do not fail at a specific load level. Here fibers fail in accordance with a series of failure events, with the weakest fiber breaking first. Fiber breakage can initiate at loads of less than half the tensile strength of the lamina.

The load taken by broken fibers is redistributed within the composite, thereby increasing the stresses in unbroken fibers. This has a knock-on effect; due to increased load, the number of fibers breaking at a given load increases. Once a number of broken fibers exceeds a threshold, the composite is no longer able to withstand any further load increment. At this point, the unidirectional lamina fractures. Such a failure can occur in at least three different failure modes:

- brittle failure of fibers, in which the fiber exhibits a brittle failure;
- fiber pullout, in which the fiber pulls out of matrix due to debonding of fiber and matrix; and
- shear failure at interface-matrix location and/or matrix debonding from the fibers.

Defect and failure investigations on aircraft structural components have an important role in improving aircraft safety. The identification of the primary cause of failure and the subsequent analysis enable recommendations for corrective action to be made. These will subsequently prevent failures from occurring in the future. Preventing failure of aerospace composites has so far yielded the following general guidance:

- align fibers with the direction of loading,
- avoid shear loading,

- use core material covered with a strong composite layer,
- combine several components into an integral structure,
- avoid high temperatures, and
- consider manufacturing operations early in the design phase.

But what future guidance for preventing failure will future case studies and analysis give us?

Despite their high strength/stiffness, low weight-to-strength ratio, wear resistance, good impact resistance, toughness, and good weather resistance, composites have not been without problems in aircraft structures. By their nature, composites are typically difficult to inspect for defects. Some absorb moisture and some components are difficult to repair, whereas traditional aluminum has a relatively high fracture toughness, allowing to undergo large plastic deformation before failure. Composites are less damage tolerant and undergo very little plastic deformation before fracture.

It is only through carrying out a systematic analysis of failures that factors responsible for an accident can be determined and preventive actions initiated. These failure analysis case studies are vital for the engineering profession and the sector. The objective is to minimize at design and manufacture of component failure probability of failure to the minimum. In the aerospace sector, when we factor in operationally complex stress cycles, manufacture, inspection, service condition, and extreme environmental variability, then there are still many unknowns. The exciting field of composites used in aerospace sector is one that offers us a complex new family of materials to study. There is a lot to learn, only time will give our profession the experience required to optimize their usage and operation.