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J1Or2B-03: [Invited] Multi scale systematisation of damage and failure modes of cryogenic composite hydrogen vessels according to the Fault Tree method

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The sustainability of the energy sector is becoming increasingly important in the face of ongoing climate change. Given the rapid growth rate of the aviation industry, it is imperative to decarbonize aircraft propulsion in order to meet the goals set forth by the Air Transport Action Group (ATAG) of a 50% reduction in CO_2 aircraft emissions by 2050 compared to 2005 levels. Hydrogen propulsion is considered the most viable technology to achieve this target, with the demand that short to mid-range hydrogen aircraft will be operational by 2035. To facilitate this swift development, an efficient development and transition process must be established.

A key enabling technology component for the implementation of hydrogen aviation is the hydrogen storage. For this application the gravimetric storage density, which refers to the energy content per unit mass of the entire storage vessel, is particularly important. To meet the gravimetric storage density requirements of medium to long-range aircraft, hydrogen must be stored cryogenically. The construction material is a crucial factor that affects the overall vessel mass. Utilizing carbon fibre reinforced polymers (CFRP) instead of metals allows for a reduction in tank mass and offers improved material resistance against degradation due to hydrogen.

Composite materials allow for a multitude of parameters in design, material, and manufacturing to be tailored for the specific use case. These advantages result in a high degree of freedom in geometry and design of cryogenic hydrogen vessels. Albeit composite materials exhibit complex interacting failure modes, such as delamination, matrix microcracking and fibre failure, potentially leading to a system hazard, depending on the severity and the type of failure mode. These mechanisms depend on the design, material, and manufacturing parameters and are also affected by the environmental conditions that may influence the material properties or introduce overloads. Complex interactions and interdependencies lead to significant uncertainties within the design process, resulting in high safety margins and therefore low gravimetric efficiency of the cryogenic hydrogen vessel.

The proposed article introduces a novel approach for the systematisation and analysis of potential failure mechanisms and interactions across length scales of the cryogenic composite vessel based on the *Fault Tree method*. Initially, the boundary conditions of the system are defined. A hierarchical system model, spanning across the length scales from the overall cryogenic vessel at the system level to individual components such as liner, inner/outer shell, insulation, and balance of plant components, and further down to the element level of the composite material and the micro-material level, is established. The environmental conditions considered include mechanical, thermal, medial and radiation loads in flight operation.

Subsequently, potential failure mechanisms of the cryogenic composite hydrogen vessel are systematised across the length scales. Typically, failures originate from phenomena at the micro-material level, like residual stress or degradation of mechanical properties, triggered by external loads or manufacturing defects. With a certain probability, these phenomena result in the initiation of a failure at the micro-material level, which may then propagate throughout the various length scales up to the system level. This approach provides a means of analytically evaluating the failure probabilities of the entire cryogenic composite hydrogen vessel, considering both structural failure modes and their interactions, as well as functional failure modes of specific components, such as valves. This enhanced insight into the failure mechanisms, their propagation throughout the length scales of the system and the impact of external influences facilitates the derivation of requirements for system design, material, manufacturing and testing. As a result, this enables an efficient development process, while significantly reducing the uncertainties of the cryogenic composite hydrogen vessel and enhancing the gravimetric efficiency without compromising safety.

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