Liquid Hydrogen Storage Tank Loading Generation for Civil Aircraft Damage Tolerance Analysis

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Abstract. The study presented is a preliminary approach and a proposal to the derivation of a loading spectrum for fatigue and damage tolerance analysis for civil aviation Liquid Hydrogen storage tanks. It is anticipated for the first generation of LH2 storage tanks for aviation to utilize metallic lightweight materials. Existing solutions are either too structurally heavy or with a short life span, both constraints making them unsuitable for aircraft vehicles were less mass and longevity is of paramount importance. The objective of the work was to provide suggestions for the generation of representative loading spectra for storage tank fatigue and damage tolerance preliminary design analysis and sizing.

1. Introduction

Liquid Hydrogen (LH2) has been regarded as a promising propellant solution for aviation decarbonization [1-5]. LH2 storage takes place at about -253^{o}C, and its cryogenic storage has been successfully engineered for land-based applications [6], marine vehicle transportation [6] and for the space industry sector. The storage solutions that have emerged so far are either too heavy or with a short life span from a structural perspective, both constraints making them unsuitable for aircraft vehicles were mass and longevity is of paramount importance. Lightweight LH2 storage solutions using composite materials have matured enough to the point of their structural integrity lasting for more than a few dozens of thermomechanical loading cycles [7,8]. It is anticipated that the first generation of LH2 storage tanks for aviation to utilize metallic lightweight materials that have been proven in service [2]. The LH2 storage solution is aimed at operating at a constant absolute internal pressurization environment, to avoid unnecessary liquid phase boil-off. The tank will constantly feed the vehicle's propulsion system, providing different fuel flow rates based on the propulsion power demand, while heat will constantly ingress from the external environment. These external disturbances to the thermo-fluid dynamic system, will generate thermomechanical pressure fluctuations to the tank structure. The objective of the work presented herein, is to propose a simplified approach to the generation of a fatigue loading spectrum of the cryogenic storage tank subjected to the environmental disturbances and operational mission loading whilst being supervised by a pressure control system. The loading spectrum generated, is aimed to be used for preliminary structural damage tolerance design, analysis and sizing.

2. Liquid Hydrogen storage tank design and materials

Hydrogen must be stored at about -253°C or lower, to be at its liquid state at atmospheric sea level pressure. At such ambient conditions, LH2 density would be approximately 70kg/m^3. Even at such extreme cryogenic temperatures, LH2 will occupy four times the volume of current hydrocarbon aviation fuels with an equal amount of combustion energy content, while the overall Hydrogen mass stored would weight 2.8 times less. A more detailed comparison of various alternative fuels, including Hydrogen, versus hydrocarbon aviation fuels can be found in [9].

Liquid Hydrogen storage has been successfully demonstrated for land applications [6] and space [10], and many examples are currently available for testifying to the successful cryogenic storage technology performance and levels of operational safety [10-12]. The automotive and marine vehicle technology has equally progressed the cryogenic storage [6] that subsequently utilize Hydrogen as fuel in internal combustion engines [13].

Heat insulation is a critical component for the cryogenic storage function, since the ambient conditions externally, are transferring heat into the structure and the stored cryogenic substance, leading to boil-off and eventually to energy loss. Most of the storage tanks are designed as double walled, also called Dewar tanks, having layers of insulation materials in between an inner and an outer tank shell. The insulation materials are of various types and technologies like foams, aerogels, reflective foils and for some designs even vacuum is used. While the inner shell contains the cryogenic liquid and vapour under pressurization, the outer shell function is mainly for protecting the insulation or to retain vacuum and it is not always required as in the case of space shuttle tanks. The discussion in the study herein focused on the inner tank shell, the one in contact with the cryogenic Hydrogen. In fig.1, the front and side views of a conceptual cylindrical LH2 tank design with toroidal end domes is shown, the inner and outer shells and the insulation in between as a crosshatched region. Also shown in fg.1, are potential locations of thermomechanical supports to provide with rigid connection between the two shells. These supports ensure the load transfer between the outer and the inner shells, with the outer shell being rigidly attached to the fuselage, while the insulation alone will not be allowed to act as the sole mechanical interface between the two shells. Once the two shells are mechanically attached, thermal coupling unavoidably comes into the picture, hence these supports must be designed to minimize heat conduction.

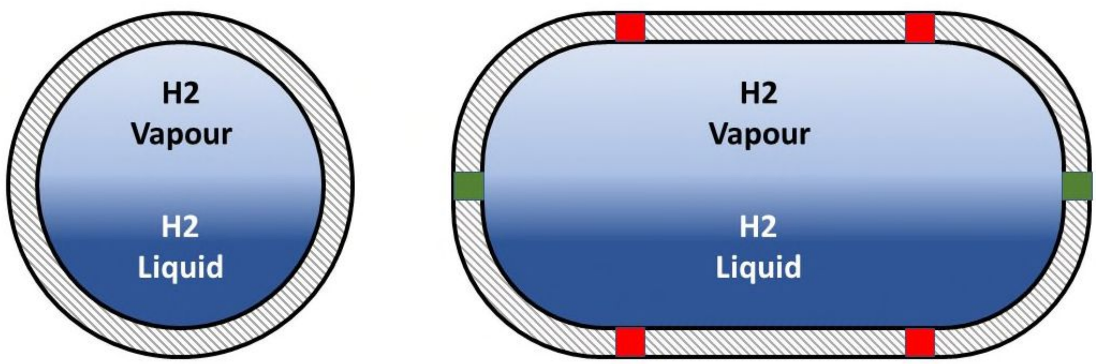

Figure 1. Front and side views of conceptual LH2 storage tanks. Liquid and vapour Hydrogen, inner shell, insulation, and outer shell shown. Indicative peripheral or axisymmetric positions of potential inner-outer shell thermomechanical supports shown on the side view

The circumferential supports, shown in red, have been used in marine applications while the axial supports, shown in green, at the domes are a classic approach for automotive vehicles. The function of these supports is to transfer the mechanical loading resulting from the inertial loads the mass of tank with the fuel will be subjected to, as well as allowing for the relative movement between the two shells due to the thermal contraction of the inner shell.

Most cryogenic storage applications currently are using metallic materials for the inner shell. Metallic materials are prone to Hydrogen embrittlement, a process where a reduction in the material fracture toughness occurs. For that reason and due to the cryogenic temperatures, austenitic steels and aluminium materials are mostly used, where the reduction of fracture toughness is less profound, attributed to their face centred cubic crystal molecular arrangement. Fibre reinforced composite materials have been successfully tested to withstand only a few thermal cycles before microcracking in the material leads to Hydrogen leakage [7]. Nevertheless, the design of a LH2 tank for aviation is feasible [15] and many key industrial players [1] have embarked upon tailoring the tank design to the aviation specific industry requirements.

3. Liquid Hydrogen storage tank operation for aviation

Aviation is looking to utilize Hydrogen as propulsion fuel, either through combustion in internal combustion engines and gas turbines, or via electricity producing fuel cells to power electric motors [1-4]. The cryogenic liquid Hydrogen has to be contained without leakage at the required temperature, whilst its storage pressure has to be controlled within an acceptable range. A feed system within the tank will provide the required fuel mass according to the scheduled propulsion needs. Liquid Hydrogen cannot be readily used at cryogenic temperatures neither for combustion nor at the fuel cells, hence fuel conditioning is required. Fuel conditioning is regarded as a separate function, and it will not be further addressed within this study.

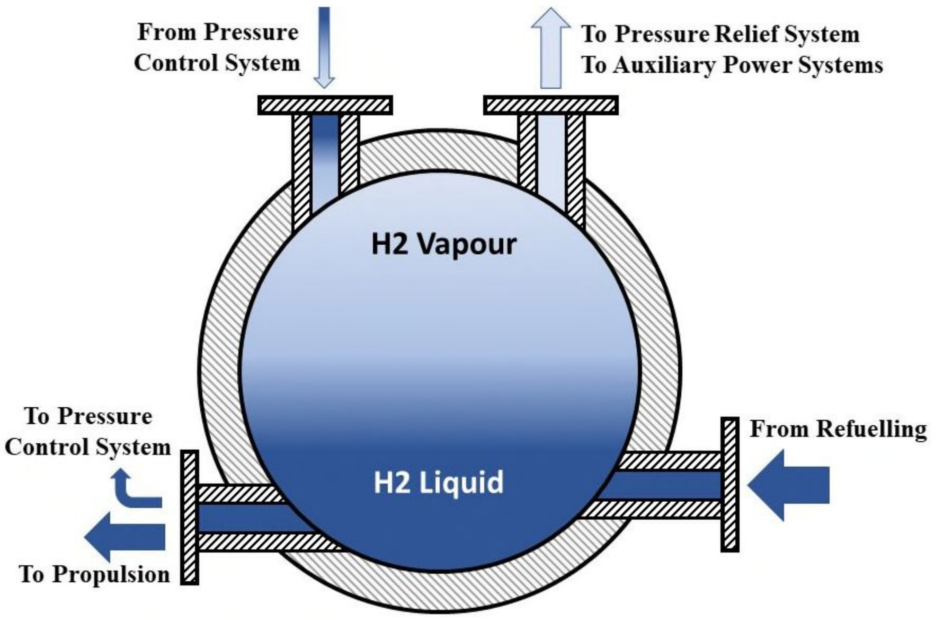

Figure 2. Conceptual design indicating the fuel tank operation

Within the storage tank, there will be a mixture of liquid and vapour phases. Pressure within the tank is controlled through the vapour phase. When there is an overpressure in the storage system, Hydrogen vapour is exhausted via pressure relief valves that is either further utilized in secondary power systems or is re-directed to a liquefaction system. When there is a reduction in the pressurization, a pressure control system will extract a small fraction of the liquid phase, evaporate it and feed it back into the storage space.

There is a consensus for LH2 storage systems to operate under a constant storage pressurization. Retaining the storage system pressurization constant is of utmost importance since the substance saturation temperature, the temperature of transition from liquid to vapour and vice versa, is controlled by the pressure. In the case of a storage depressurization, the liquid phase will tend to evaporate

adding to the system pressurization that could even lead to structural damage during extreme depressurization rates [14].
Hydrogen can exist in the form of orthohydrogen and parahydrogen, related to the direction in the spin of the atoms in the molecule. Liquefaction plants will provide Hydrogen in its parahydrogen form. The phase diagram in fig.3 depicts the saturation dome indicating the saturation pressure-temperature correlation. Tracing the 1bar dotted line from ambient temperature conditions at the right bottom of the chart in fig.3, by removing enough heat under a supposed isobaric process thus moving to the left of the chart on the 1 bar dotted line, the saturation curve is reached (point 1 on the chart) displayed as thick lined dome. At that temperature point, which for 1bar pressure is close to -253ºC/20K, additional heat removal depicted as moving from point 1 to point 2 on the chart, is not affecting the temperature of the Hydrogen since condensation has started until the other point in the dome is reached where the substance will be completely liquefied (point 2 on the chart). The saturation temperature is specific for the pressure Hydrogen is subjected.

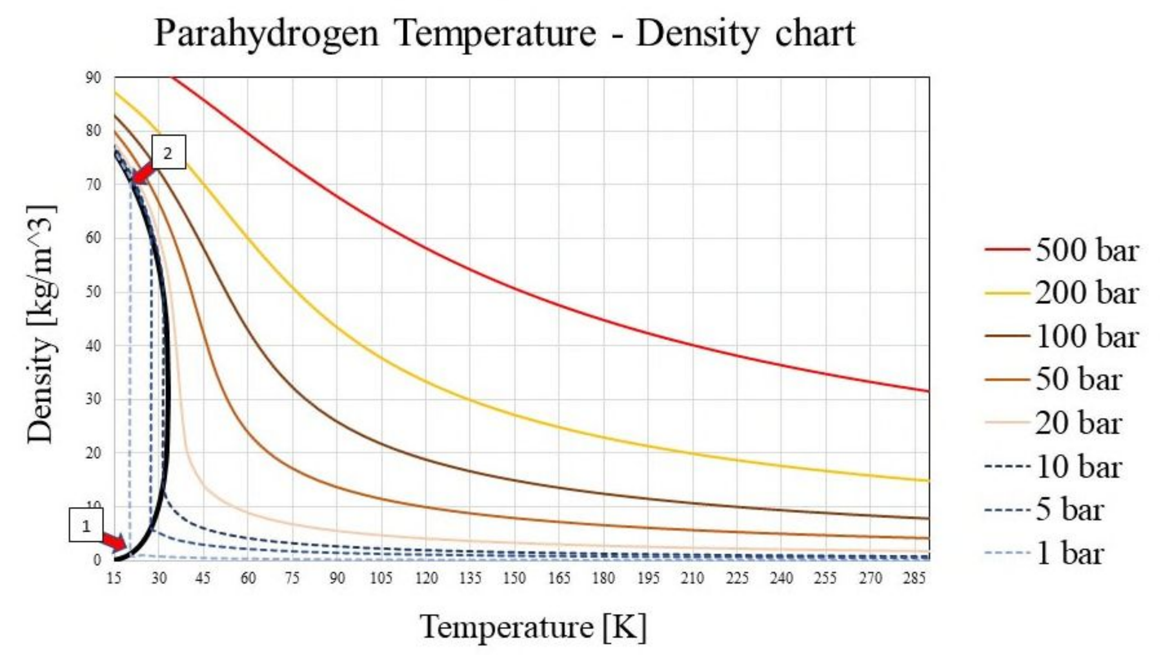

Figure 3. Temperature density and pressure phase diagram for parahydrogen [16]

An alternative approach to absolute constant storage pressurization, is the constant gauge pressurization where the differential pressure between the internal pressure to the external ambient of the inner shell is retained at a constant level. A system operation of that sort would require the liquid within the tank to be cryocooled to the saturation temperature of the smallest pressure to be met in service, else the system would not have the capability of reducing its pressure.

4. Liquid Hydrogen storage tank loading generation for aviation

The operating conditions a LH2 storage shell in direct contact with the cryogenic Hydrogen, can be described as a constant storage positive pressurization about which smaller pressure variations will take place due to the pressure control system and the aircraft operation. The main loading sources of the pressurized and cryogenic inner structural shell for the derivation of the fatigue spectrum are accounted for below:

Storage pressurization and refueling – low cycle, large stress variation, R=0

A typical civil aircraft mission would commence from sea level altitude conditions, climb to the maximum flight altitude ceiling level for the aircraft type and mission, and decent back to sea level conditions at the end of the flight journey. The storage pressurization must be selected to always be higher than the sea level atmospheric one, to avoid atmosphere entering the fuel system in the event of structural damage. Depending on the choice of using vacuum or not for insulation and depending on the cruise altitude, the pressure differential between the storage pressurization and atmospheric conditions responsible for the shell stressing can be evaluated. For demonstration purposes, the storage pressure is assumed as 1.1bar herein. In the case the storage tank is making use of vacuum technology for insulation, then the pressure differential acting on the tank walls is 1.1bar irrespective of the cruising altitude. This pressurization level will cycle once every flight during refuelling and once when tank emptying, and inspection takes place. If a vacuum technology is not used, the pressure differential would be about 0.1bar at sea level altitude, and about 0.8bar at a cruising altitude of 30,000 feet.
For both cases, the cycling nature of the pressurization load can be determined since it is closely related to the actual number of flights. The stress level variation is relatively large and under normal operation this will provide a positive mean stress ($R = \sigma_{min}/\sigma_{max} = 0$) about which the other stress fluctuations will take place.

Pressure control system – high cycle, small stress variation, R>0
The pressure control system function is to retain the appropriate internal storage absolute pressurization levels; in this study we have assumed that value to be equal to 1.1bar. If the aircraft is not in operation, heat ingress from the surrounding environment will heat up the Hydrogen in the tank, both the liquid and vapour phases, leading to thermal expansion and evaporation. This effect will contribute to the rising of the internal pressure which can be allowed up to a certain maximum allowable pressure value. Past that, Hydrogen vapour could be internally exhausted from the tank via pressure relief valves, either to be utilized in a secondary power source or to be driven to a liquefaction system or plant for re-condensation. When the aircraft will be in operation, the liquid will flow towards the energy consuming engines hence the pressure will drop in the tank. A control system will bypass a part of the liquid phase, evaporate it and feed it back inside the tank. The control action aims to stabilize the pressure level about its absolute internal pressure, but there will be several fluctuations about that pressure level every time the control system is triggered, depending on the dynamic response of the system architecture. This type of fatigue loading is characterized as high cycle, small stress variations about a mean stress. A dynamic model for evaluating the control system performance has been described in [17, 18] that can be used to trace the pressure fluctuations of a LH2 storage system. But even without such software, a reasonable assumption of a number of fluctuations based on the system's inertial response until system resting between two extreme stress values can be assumed. For example, if a pressure relief valve is triggered, a rough estimation of a few tenths or hundredths of cycles about the max-min valve settings can be assumed in a conservative manner. Similarly for the control system triggering and response.

Aircraft ground maneuvering, flight loads and gust response – high cycle, small stress variation R>0
Widely accepted standardized methodologies for deriving the structural loading when on ground or during flight [19-21] can aid towards the generation of a typical loading spectrum in the form of acceleration at the location of the storage tank. Depending on the storage tank and fuel combined weight as well as the type and location of the supporting arrangement on the fuselage, the additional stress variations can be evaluated. Aircraft ground and flight loads typical random distribution can be employed. The structural excitation due to the loading will die out according to the structural dynamic behaviour of the tank. Similarly to the previous category, the stress variations are much smaller than the mean stress caused by the internal pressurization and are expected to be in the high cycle occurrence regime.

Thermal stresses from material expansion and contraction
Stresses arising either from structural differential expansion/contraction or due to the obstruction of, must be eliminated. It is of utmost importance for the tank and supports design to allow for the unconstrained structural motion resulting from temperature differentials. At the same time, the outer shell has to be securely attached within the aircraft fuselage and be capable to carry the tank weight and fuel storage inertial loads over to the main load carrying members.

5. Discussion on the damage tolerance preliminary design of a metallic LH2 tank shell

The inner cryogenic and pressurized LH2 tank shell made of metallic materials must be designed with appropriate levels of structural integrity. The structure must tolerate initial flaws of a certain inspectable threshold. The structure must be capable of withstanding damage propagation for a certain life span, potentially prolonged with the appropriate structural health monitoring technologies in place. Additionally, the structure must exhibit a leak-before-burst type of failure, meaning that large enough through-thickness cracks that will allow Hydrogen to leak must be tolerated by the tank shell, well before fracture occurring. The first design constraint relates to material crack growth curves and the latter with the material fracture toughness. Both material properties must be derived at cryogenic temperatures under Hydrogen exposure, though material properties data of that kind are currently unavailable in the public domain, or they are rather old in the need of updating. References exist that report of certain alloys fracture toughness and crack growth curves not to be significantly affected by Hydrogen [22] even to show a better performance, but a wider cross referencing and correlation with updated experimental research in the proper environmental conditions are needed. Discussion will proceed assuming similar fracture toughness and crack growth response to Al alloys.

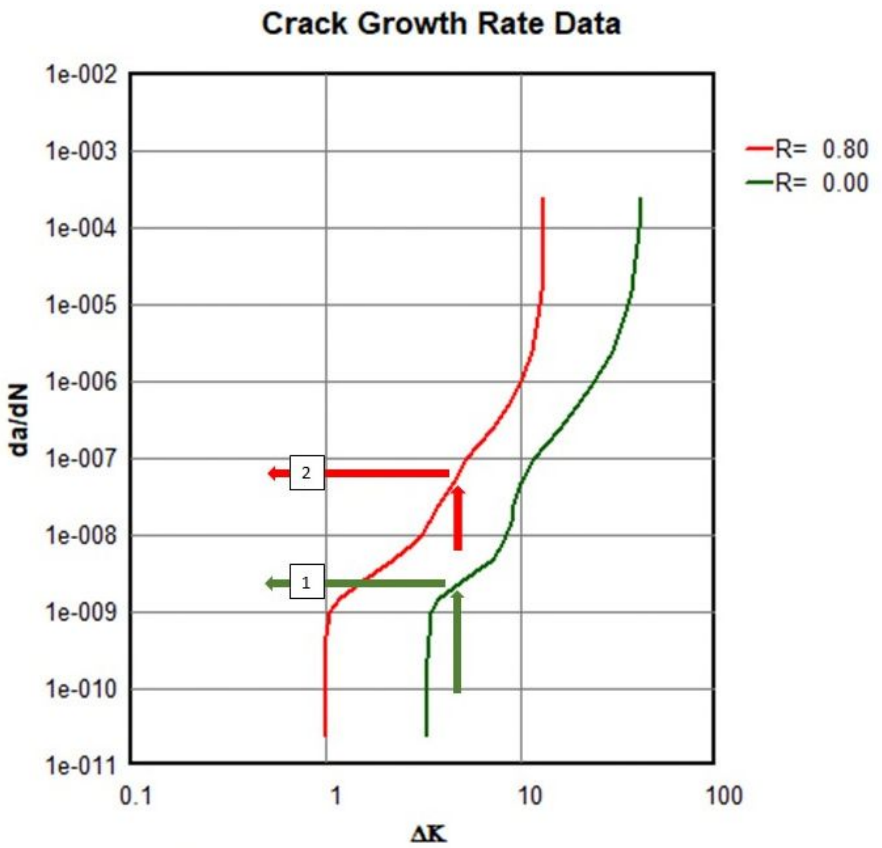

Figure 4. Example crack growth curves for AL-2024 at different R ratios [23]

Depending on the differential pressure on the inner shell and the diameter of the tank, the tank wall thickness can dictate the membrane stresses on the skin. The allowable membrane stresses can be derived from assuming that a through the thickness crack, enlarged by a factor of safety, will not cause spontaneous fracture of the shell based on the material fracture toughness. Depending on the initial part through thickness flaw size assumption until its growth to a through thickness flaw that will lead to Hydrogen leakage and a safety factor on the crack size, the tank life can then be estimated based on the fatigue loading described in this study.
Figure 4 shows example crack growth curves of Al-2024 at ambient temperature, for two different R ratio values, with R being the min over the max stress in loading cycle. The curve with the higher R ratio resembles the high cycle loading from the pressure control system functioning and the aircraft loading. The crack growth rate data clearly show that for the same stress variations about a non-zero mean stress value, the one with the higher R ratio is considerably more damaging to the structure.
Another observation from figure 4 is that for low values of ΔK, practically for low values of stress variation, the material performance is at the range of no significant crack growth rate. As a conclusion to this paragraph, it is critical for the research community to experimentally derive the material fracture toughness and crack growth rate curves for the candidate materials for LH2 tanks, in a Hydrogen cryogenic conditions environment.

6. Conclusions

In the study herein, the components of typical loading for an aircraft fuselage mounted LH2 tank were explored, for usage in aircraft preliminary design. The study suggested a method and assumptions to preliminary quantify the individual loading components for deriving a simplified loading spectrum generation for fatigue and damage tolerance analysis.
The critical components in the evaluation of the remaining structural life, was the material fracture toughness and the actual crack growth behaviour in cryogenic temperatures, in the presence of Hydrogen, data which are not that widely available in the public domain. The study nevertheless highlighted the R ratio and ΔK regime of interest for the experimental testing to focus upon. It is anticipated that understanding the material behaviour for the high-cycle, low stress variation about a mean stress will be the important component in the crack growth assessment of LH2 tanks, especially when total life will be terminated by a crack growing from part to a through-the-thickness size.

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