Liquid Hydrogen Storage Tank Virtual Crashworthiness Design Exploration for Civil Aircraft

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Abstract. Civil aviation industry is researching for alternative fuel energy sources to substitute current hydrocarbon-based aviation fuels. Carbon free emissions flights could be achieved with fuels like Hydrogen either through combustion or via electricity producing fuel cells. It is of great importance to explore the airframe designs to house Hydrogen in its cryogenic liquified state. The objective of the study herein was to provide a conceptual qualitative analysis related to the crashworthiness behaviour of civil aircraft carrying liquid Hydrogen fuel storage tanks. The design parameters of interest were the storage tank location in the airframe, the structural energy absorption following crash landing scenarios and the structural deformation of the structure surrounding the tanks, penetrating the survival space of the occupants. Several structural design arrangements were proposed and compared. Simulation results indicated that the optimal location for the fuel storage greatly depends on the actual aircraft layout as well as on the future civil aircraft airworthiness requirements that are still under development for that type of fuel energy source.

1. Introduction

Liquid Hydrogen (LH2) has been regarded as a promising propellant solution for aviation decarbonization [1, 2]. Its properties make it a suitable candidate with adequate energy density for typical aviation mission utilization, but it needs four times the current aviation hydrocarbon fuel storage volumetric space it is meant to substitute. Airworthiness certification requirements for Hydrogen propellant in aviation are currently under development, hence there is no clear guidance from the aviation safety authority perspective in terms of the design and usage of such fuels, fuel systems and aircraft design and operation in general.

It is of great importance to explore the airframe designs to house the LH2 storage system. Due to various design constraints for the pressurised LH2 cryogenic tanks, there is a strong possibility for the storage locations to be within the aircraft fuselage cross section. The focus of the research presented herein, was to study the crashworthiness performance for several proposed airframe designs housing LH2 storage tanks. The design parameters of interest were the structural energy absorption due to downwards airframe crash scenarios and the structural deformation of the structure surrounding the tanks, penetrating the survival space of the occupants. Several structural arrangements were proposed and compared, which were developed based on the Airbus A350 long-haul aircraft fuselage cross section properties [3]. The dominant design proposal arrangement is that of a stretched fuselage that allows the installation of several tanks within the existing fuselage section cavity. In fig.1, an aircraft similar to a supposed modified Airbus A350 is shown, where some additional fuselage sections are added to the front and to the rear from the aircraft centre of gravity, producing an elongated version of the aircraft.

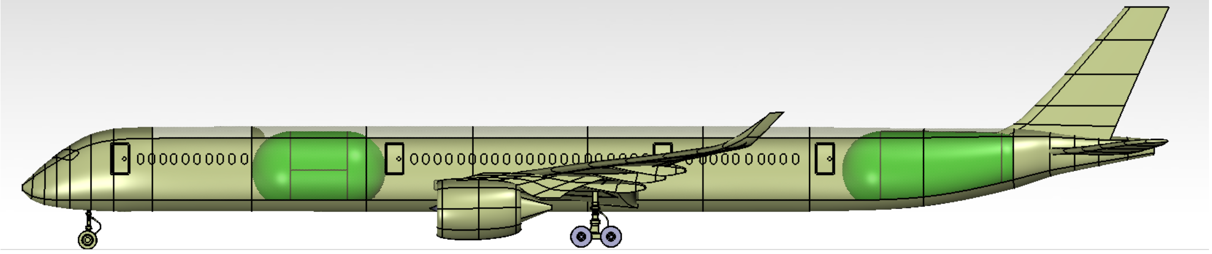

Figure 1. Elongated fuselage for providing storage space for LH2 fuel

In this configuration, adding 15m to the baseline fuselage length, allowed to store enough LH2 inside the fuselage for a typical flight mission. To control the aircraft centre of gravity, one tank was located forward of the wing and the other afterwards. The fuselage cabin layout was laid out in the following order starting from the nose of the aircraft: pilot cockpit, business class, forward tank, economy class and aft tank. The overall aircraft length was modified to 77m, which is equivalent to the longest long-haul aircraft on the market currently.
An alternative proposal to the elongated fuselage was based on the conceptually designed Cryoplane project [4], which was modified herein as having the same cross-sectional characteristics to the Airbus A350 aircraft, with an additional protrusion on the top of the fuselage to house the LH2 storage.

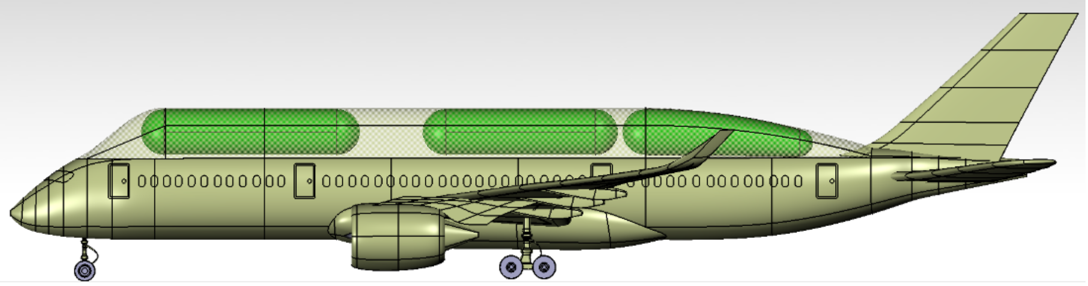

Figure 2. Overhead storage modified aircraft having a protrusion on the top of the fuselage for storing LH2 fuel

LH2 tanks were stored above the cabin in a double-deck configuration. There was no need to pressurise the upper deck. Potential engine fragment trajectory was considered by allowing for a gap within the tank cascade. A bigger tailplane was designed due to the increased cross section. The overall aircraft length of 62m was similar to the shortest long-haul aircraft on the market.
In fig.3, the two dominant design proposals are shown for visual comparison. These designs can carry the same amount of LH2 fuel.

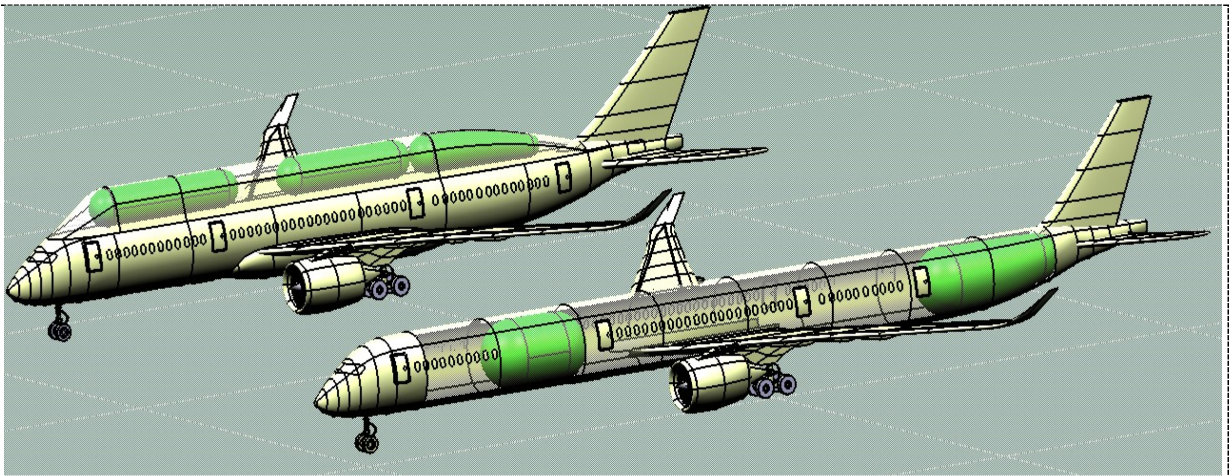

Figure 3. The two dominant aircraft designs for storing LH2 and use Hydrogen as propellant fuel

2. Conceptual design and analysis

A conceptual aerodynamic initial approach based on simplistic empirical formulae was applied to analyse the drag generated in cruise conditions. The results showed that both aircraft design features contributed to an increased drag penalty with respect to the original unmodified aircraft version. The elongated fuselage was adding more friction drag due to a larger wetted area, while the overhead storage version increase in the drag was mainly from the larger frontal area. A more rigorous analysis would be required to fully understand the aerodynamic impact of the two configurations, like a 3D vortex lattice numerical approach. Such an approach was left out of the scope of the present conceptual study.

The conceptual analysis also indicated various pros and cons to each of the proposed designs. Changes in the fuselage design and overall aircraft weight, induced changes to other major aircraft components like the wing size, engine thrust to aircraft weight ratio, horizontal and vertical stabilizers sizes, landing gear weight etc. A major issue for flight stability was the aircraft centre of gravity movement during mission. Both designs considered fuel mass to the front and to the rear of the aircraft centre of gravity, hence they were both capable to control the aircraft longitudinal stability during flight. Even if the fuel was not evenly distributed about the centre of gravity, flight control systems could be designed and create aircraft configurations that meet the stability requirements through flight control stability augmentation systems, at the expense of possible additional aircraft drag and a more complex flight controls for ensuring the required levels of safety.

For the elongated configuration, the tanks stored within the fuselage were much closer to the ground in the event of a crash landing. For the overhead configuration, storage tanks must take into consideration the possibility of an engine failure potentially rapturing the tanks, hence there was some unused space in the overhead fuselage to cope with the engine fragment trajectories.

Overall, the conceptual analyses performed for the elongated and the overhead storage fuselages, indicated that although both designs had drawbacks regarding the original, unmodified, and streamlined aircraft version, they nevertheless offered plausible solutions for initial design to commence. In the future, the aircraft design concepts to operate on Hydrogen fuels may well deviate from the classic tube-and-wing traditional concept and resemble more a blended wing design. Such a solution would take into consideration the storage tanks earlier in the conceptual design cycle and potentially result to a more flight efficient overall solution. The below figures 4-7, indicate the attachment positions on the storage tanks for the two configurations, along with their supporting bulkhead structures.

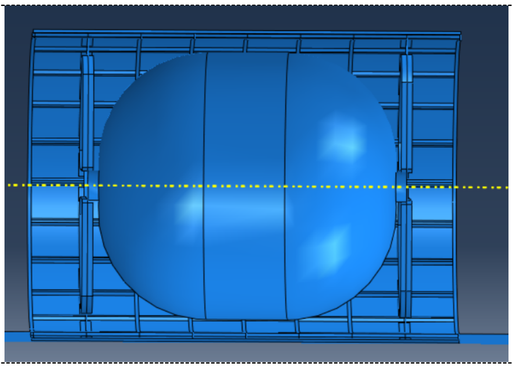

Figure 4. Elongated fuselage LH2 storage tank of a cylindrical design with domed ends, framed within two supporting bulkheads on either end

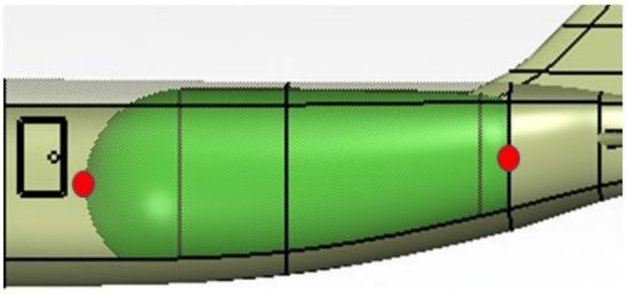

Figure 5. Elongated fuselage aft tank of a tapered design, to better match the aircraft internal cavity. Attachment locations are indicated

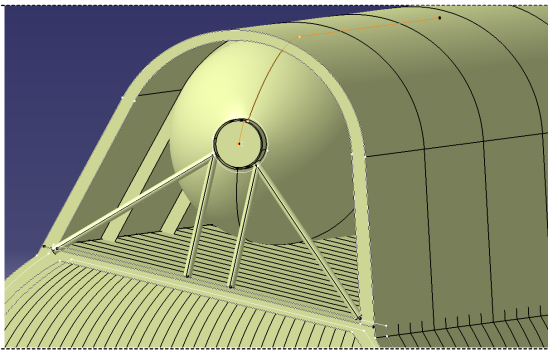

Figure 6. Early four compression rod overhead storage fuselage attachment design proposal

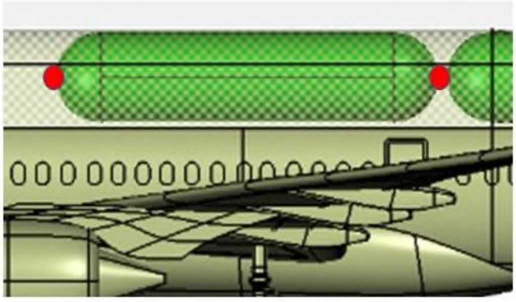

Figure 7. Overhead storage fuselage attachment positions at the forward and rear dome ends

3. Virtual testing for design exploration and pre-certification studies

The study herein aimed at providing insights to the fuselage crashworthiness behaviour of fuselage structures housing LH2 tanks, and to assess the requirements compliance as dictated from the current safety and airworthiness certification authority [5]. A qualitative assessment was derived and presented in the conclusions section of this document.

The airframe must be capable of retaining certain levels of its structural integrity in the event of survivable crash-landing scenarios [5]. A good understanding of the aircraft crashworthiness has been developed by the airframe research and design industry [6-12], studies that are complemented by test results available in the public domain [13]. It is highly likely for the current airworthiness requirements to be reviewed and amended for Hydrogen propelled aircraft regarding crashworthiness, but the current study made use of the existing requirements framework.

Latest trends in the means of evidencing compliance with requirements, contain an ever-larger portion of virtual structural testing, that are numerical finite element model simulations. Virtual testing provides a cheaper means to actual testing for design exploration and is recently incorporated much earlier in the design lifecycle.

Various numerical finite element models were built, and crash scenarios were simulated, for growing the understanding in the structural arrangements required for showing compliance to the required crash behaviour. Finite element explicit analyses were performed using nonlinear progressive damage in Abaqus software [14]. Early stages models aided with the design envelope exploration for down selecting the most important structural features participating in the crash simulations. Examples of such models are shown on figures 8 and 9.

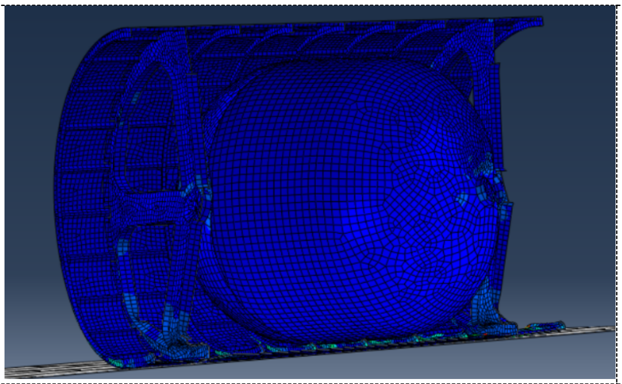

Figure 8. Preliminary virtual crash testing analysis and structural response. Early design stage attachment, incorporating a cross design bulkhead

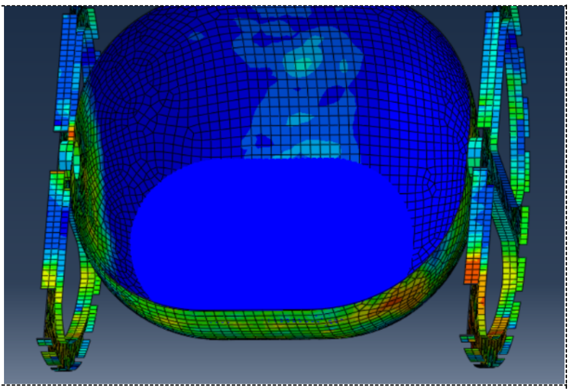

Figure 9. Simulations modelling the sloshing effect of the stored fuel in the tank, using Spherical Particle Hydrodynamics method

Following the more generic models like the ones shown on figures 8 and 9, the design aim was then centred around tailoring the structural elements of the supporting structure. These are fuselage frames, circumferential metallic fuselage ring type structural components, shown on figures 10 and 12. Such frames are often referred to as bulkheads, if they separate fuselage compartments of different pressurization, which may or may not be the case for the proposed elongated design. Crash behaviour is more efficient in metallic structural components, where material plasticity is utilized as the means for energy absorption. It was decided for the first generation of frame supporting structures to be designed using metallic materials although fibre reinforced composites could be employed in some of the designs as well. There are two major structural failure modes most often used for energy absorption, the axial compression crushing and the plastic hinge bending modes. The fuel storage tanks will be attached at the end domes, as shown on figures 5 and 7.

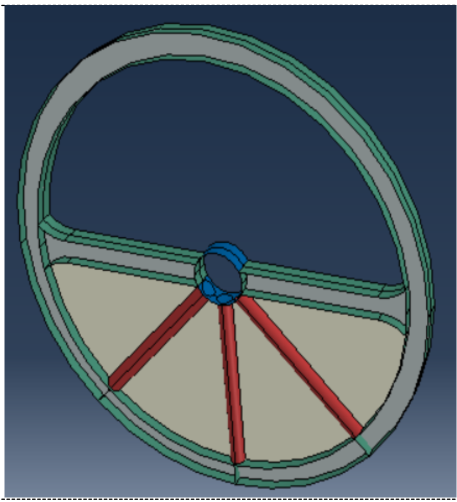

Figure 10. Fuselage frame with a central attachment position for the elongated version aircraft design storage tank. Structural elements to absorb energy in different modes, compression and bending

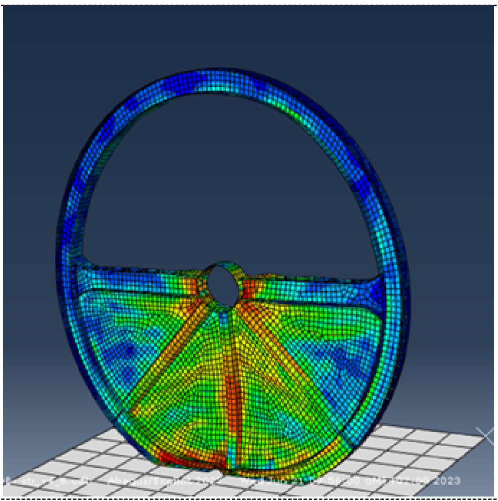

Figure 11. Representative model of a downward crush scenario, used to evaluate the failure sequencing based on the structural elements design, geometry, and material properties

To model a downward crash landing, a vertical initial velocity of 11m/s was applied according to CS25.562 guidelines [5]. The design objective for the elongated fuselage was for the support location at the centre to travel less than 200mm in downwards displacement, while for the overhead tank was 500mm. At each support location, a point mass of 15 tons was attached to simulate half the structural weight of the tank and fuel contained within. The models were meshed with quadrilateral shell elements (S4R), and an isotropic bilinear plastic material behaviour.

Following an iterative process, the major structural elements to engage in the crash process were triggered along with their geometric properties. For the elongated fuselage, axial compression beams with buckling initiators were selected as the first line of structural collapse, supported by a thin shin to better control the collapsing modes on the same plane.

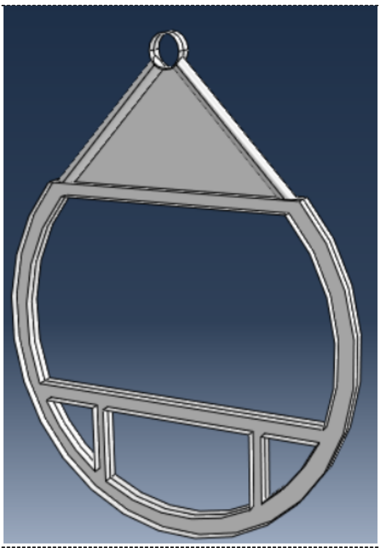

Figure 12. Fuselage frame with a one side central attachment position for the storage tank. Design variant with side struts, without a central strut

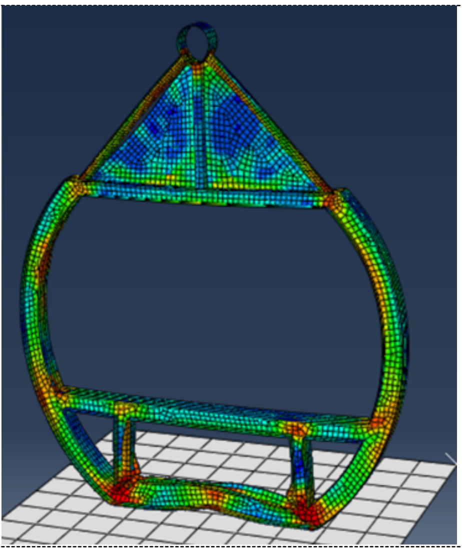

Figure 13. Representative model of a downward crush scenario, used to evaluate the failure sequencing based on the structural elements design, geometry, and material properties

4. Results

The results indicated that the energy absorbed by the structure was greatly affected by the proposed alternative designs, as expected. Different design proposals showed different areas of strength and weaknesses with respect to the total energy absorbed by the system and to the penetration of the surrounding collapsing structure. The goal of the analysis was to compare the structural mass of the frames, needed for the critical deflection threshold. It was found that the overhead storage design to require 10% heavier frame attachments supports. Analysis needed to expand into different direction as well prior to resulting to the more efficient design solution overall at the aircraft level.

5. Conclusions

Computer simulated virtually tested crashworthiness scenarios can be used at the preliminary design stage of airframe structures for design exploration. The study herein provided insights to the crashworthiness performance for a number LH2 storage design proposals as well as it highlighted the proposed design with the best crashworthiness performance characteristics. The preliminary FEA results showed that it is possible to create crashworthy LH2 tank attachments, to comply with the current civil aviation airworthiness requirements. Creating a crashworthy attachment has a significant impact on the overall LH2 tank structural mass.

Regarding the assumptions made, the weight difference between both configuration favours the elongated fuselage design, as more that 10% of attachment structural weight could be saved at each attachment location.

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