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► **To cite this version:**

R. Parello, Yves Gourinat, E. Benard, Sébastien Defoort. Structural sizing of a hydrogen tank for a commercial aircraft. 13th EASN International Conference on: Innovation in Aviation & Space for opening New Horizons, Sep 2023, Salerno, France. pp.012040, 10.1088/1742-6596/2716/1/012040 . hal-04722390

HAL Id: hal-04722390

<https://hal.science/hal-04722390v1>

Submitted on 11 Oct 2024

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Structural sizing of a hydrogen tank for a commercial aircraft

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Abstract. To respond to the current climate crisis, hydrogen-powered aircraft are seen as a promising solution in the aviation sector to cut down CO_2 emissions. Hydrogen-fueled aircraft present however huge challenges, especially due to the complex storage of hydrogen. To achieve a reasonable fuel energy density for medium- to long-range missions, hydrogen must indeed be stored in liquid form in big and heavy pressurized tanks. Tank design must so be included in conceptual design, which now has an important impact on the aircraft. This study proposes a structural sizing methodology for a liquid hydrogen tank for a commercial aircraft. A parametric model of a cylindrical cryogenic tank placed at the back of the cabin in a conventional aircraft is created and sized to withstand pressure, bending, torsion and shear loads. The process integrates sizing standards for pressurized structures of the current CS-25 regulation in its methodology and remains general enough to consider both integral and non-integral tanks of any dimensions or materials. Initial analyses show a clear dependency of the tank's performance as well as the optimal stiffening structure configuration on the design pressure.

1. Introduction

To limit the negative impact that the current climate crisis will have on human society, countries around the globe signed the Paris agreement in 2015, promising to cut their greenhouse gas emissions to stay below a $2^\circ C$ increase on earth by 2100 and even below $1.5^\circ C$ if they can. This situation pushed the International Civil Aviation Organization (ICAO) to declare in 2022 that the aviation sector must become climate neutral by 2050, when today the aviation sector is estimated to be responsible for 2-3% of the global CO_2 emissions. However, by including the non- CO_2 effects, mainly due to NO_x emissions and contrails, it is responsible for 5-6% of the radiative forcing on earth [1] and this share is expected to grow in the future with traffic growth.

One possible solution to this problem is the use of hydrogen-fueled aircraft. Hydrogen can indeed be sustainably produced by electrolysis and doesn't release carbon at combustion or when used in a fuel cell. Hydrogen aircraft represent however huge economic, technological and safety challenges. One key problem with hydrogen-fueled aircraft is the storage of hydrogen onboard, which is probably going to affect the design the most because of the very low energy density of dihydrogen at standard temperature and pressure. To be stored in a reasonable volume on an aircraft, it will have to be compressed or liquefied, with compressed gaseous hydrogen only suited for short regional flights. Larger aircraft will most probably rely on liquefied hydrogen, which has to be stored at 20K in a pressurized tank, meaning the tank is now much more complex



and heavy. This justifies the inclusion of the tank's design in the conceptual design phase of the aircraft, as it will have a major influence on the aircraft's performance. The design of the tank can be divided into the structural and the insulation sizing and in this study only the structural sizing is covered.

Even in liquid form, the energy density of hydrogen is still low compared to kerosene, meaning that the tank has to be more than four times bigger than for conventional fuel to store an equivalent amount of energy. This, combined with the necessity to hold pressure, leads towards big cylindrical-shaped tanks, which are the most ideal shape to maintain pressure (and also limit heat influx) after the sphere. They can't however be placed in the wing anymore. An important aspect of the tank design becomes then its integration into the aircraft. In a conventional configuration, a hydrogen tank can for example be integral, i.e. a part of the fuselage, or non-integral when the tank is inside the fuselage. Previous studies interested in assessing the feasibility of hydrogen aircraft developed structural sizing methodologies for both concepts.

Brewer [2] considers the integral concept to be best in terms of mass and for inspection. He finds for example with his hypothesis that the fuel weight fraction in the integral tank was 0.927, compared to 0.855 for the non-integral tank. Non-integral tanks can also represent a big safety hazard in the event of a leak in the fuselage, where the accumulation of hydrogen could result in an explosion if the fuselage is not vented. Like Brewer, Onorato [3] finds that an integral tank is more advantageous to reduce the aircraft mass, but he is one of the few authors to model both integral and non-integral tank concepts and make a comparison at the aircraft level. Other studies very often focus on one single type of tank.

To be able to precisely design such an integral tank, a finite element analysis should be conducted, as is done by Brewer for his aft-conical tank. This requires precisely knowing the load applied to the tank by the rest of the aircraft structure, which is difficult to determine as the tank position isn't fixed in the conceptual design. In this design phase, an emphasis is also placed on using analytical models to limit computation time in order to test a wide range of designs. That's why in the cryoplane study [4], which adopts a minimal change strategy, tanks are designed with analytical models, even if they are integral tanks. Verstraete uses the same approach and sizes his tank only with respect to pressure. He uses for this the method from Barron [5] which gives the tank's skin thickness as a function of the design venting pressure and tank material properties for a cylindrical tank with an elliptical-shaped head. Onorato uses the same model to compute the tank skin thickness but also includes the weight of the tank's support with correlations from Brewer. Winnefeld et al. [6] on the other hand only consider non-integral tanks but develop a methodology to size all ellipsoid-shaped tanks where the tank is also only sized for pressure. This study shows however that an ellipsoid-shaped tank always presents a significant weight penalty compared to a cylindrical one. Except from Brewer, none of the previously mentioned studies include the stiffening structure in the tank design.

In this study, a new analytical structure sizing methodology for hydrogen tanks is developed. It is able to model both integral and non-integral tanks and takes. Unlike previous studies it sizes the tank the stiffening structure and not only the tank skin following current CS-25 regulations concerning the certification constraints on the design of mechanical structures. It remains also sufficiently parametric to enable the design exploration essential to conceptual design.

2. Methodology

The developed method to size an hydrogen tank is constructed as part of a wider aircraft multidisciplinary analysis. The method is so built as a sub-discipline in a multidisciplinary

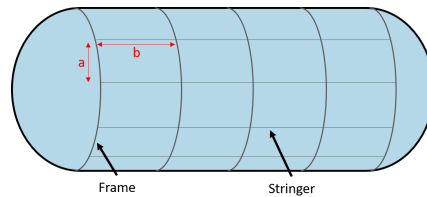


Figure 1. Representation of a cylindrical hydrogen tank and its stiffening structure

analysis, and some inputs of this method will come from previous disciplines like the mission module. With those inputs provided, the method then sizes the tank in three consecutive steps respecting CS 25.305 (Strength and deformation) and CS 25.307 (Proof of structure) regulation:

- Determination of the loads the tank will have to withstand: pressure load but also shear forces and bending moment that the tank will have to withstand. Those depends on the limit load factor, which must also be determined
- Sizing of the tank skin thickness
- Sizing of the stiffening structure

These three steps are detailed in the following parts. In this sizing process, several load terminologies defined by the current CS 25.301 (Loads) and CS 25.303 (Factor of safety) regulation are used. Those are the operation load (OL), the limit load (LL) and the ultimate load (UL). The operational load is defined as the load that the aircraft will encounter during nominal operations. The two other loads are defined relatively to this operational load:

$$UL = 2 * OL, \quad LL = \frac{UL}{1.5} \quad (1)$$

The overall logic concerning those different loads is as follows: The skin is sized to withstand the operational load alone, meaning that its thickness is sufficient to endure the pressure, the shear stress and the bending moment while remaining in the elastic domain. The skin should also not buckle under the operational load. Above the operational load, the skin is assumed to have buckled, and all the loads are supported by the stiffening structure, which is composed of stringers (longitudinal stiffeners) and frames (circular stiffeners) visible in figure 1. The stringers and frames are sized to prevent buckling at the operational load, stay in the elastic domain at the limit load, and not break at the ultimate load. Previous models found in literature tend to not consider the stiffening structure sizing and the different load cases to be considered according to the CS-25. Their final tank design can therefore be quite different, but a more complete comparison will only be possible when this method is integrated into a full aircraft multidisciplinary design analysis.

2.1. Load determination

The first step in sizing the tank is to determine the load. In this case, three types of loads are present:

- Pressure load: normal to the tank skin and equal to the pressure differential between the tank and its exterior environment, which can be the atmosphere or the fuselage interior in the case of a non-integral tank. The operating pressure is considered here as an input, and for a non-integral tank it is assumed that the fuselage part where the tank is located isn't pressurized.
- Bending and torsion moment: transmitted by the fuselage onto the tank.
- Shear stress: Shear flow also transmitted by the fuselage onto the tank.

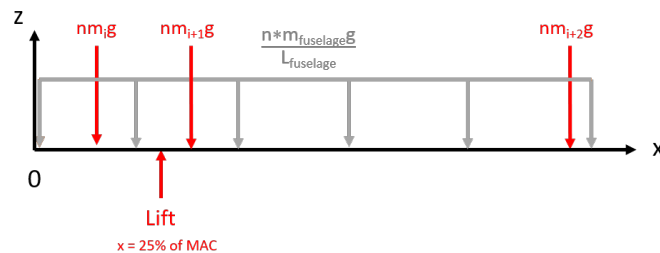


Figure 2. Beam model of an aircraft

If the pressure load is an input, it is necessary to determine the bending and shear loads that the tank has to withstand. For an integral tank, all the load will be transmitted. Non-integral tanks are modeled by modulating which fraction of the total load is transmitted to the fuselage. To compute the bending moment and the shear load, the aircraft is represented as a beam (figure 2). The weight of the different aircraft parts or subsystems is distributed along the x axis between 0 and $L_{fuselage}$, which is the length of the fuselage. The fuselage, the payload and the tank are represented as distributed weights (figure 2 shows an example with the fuselage weight). The lift is represented as a force at 25% of the main aircraft cord (MAC). It is then possible to determine the distribution of the bending moment along y and the shear stress:

$$M_b(x) = \sum_i nm_i g(x - CG_i) + \sum_i \int_{X_{start}}^{\min(x, X_{end})} \frac{nm_i g(x - y)}{l_i} dy \quad (2)$$

$$T_z(x) = \sum_i nm_i g + \sum_i \int_{X_{start}}^{\min(x, X_{end})} \frac{nm_i g(x - y)}{l_i} dy \quad (3)$$

Where n is the load factor, CG_i is the x coordinate of an element's center of gravity, m_i its weight and l_i its length if applicable. For both loads, the first sum corresponds to the single-point weight placed before x , while the second sum corresponds to the distributed weight starting before x . Only weights located before x are considered. The tank is sized to support the maximum bending moment and shear stress found in the fuselage's part where it's positioned.

The bending and shear load depend obviously on the load factor n . This load factor varies during the flight but a limit load factor can be computed according to the CS-25 regulation.

2.2. Skin sizing

Once the different moments and the shear load have been determined, the sizing of the tank's skin can occur. This requires the computation of the stress tensor in the skin.

As stated before the skin is sized to withstand the operational load alone, i.e. without considering the stiffening structure. The shear flow of the tank is however only circulating in the skin, meaning that for this load in particular, the skin will have to be sized directly to the limit load. The shear flow is due to the shear stress, which depends in turn on the angle θ (see fig. 3), and to the torsion moment and results in:

$$\sigma_{xy}(\theta) = \sigma_{yx}(\theta) = \frac{T_{z,maxLL} \cos(\theta)}{t_{skin} \pi r_{tank}} + \frac{M_{torsion,LL}}{2\pi t_{skin} r_{tank}^2} \quad (4)$$

Where t_{skin} is the tank's skin thickness, r_{tank} its diameter, $M_{torsion}$ the torsion moment and $T_{y,max}$ the maximum shear stress along the tank, computed with the limit load.

In addition to the shear flow, the bending moment and the pressure also contribute to the stress. The resulting stress tensor is [7]:

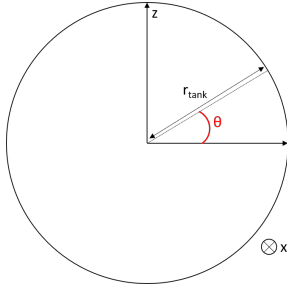


Figure 3. Tank's section parametrization

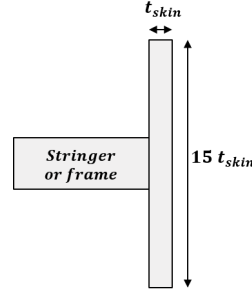


Figure 4. Example of a super stiffener's section

$$\Sigma(\theta) = \begin{pmatrix} \frac{\Delta P_{OL} r_{tank}}{t_{skin}} & \sigma_{xy}(\theta) & 0 \\ \sigma_{xy}(\theta) & \frac{\Delta P_{OL} r_{tank}}{2t_{skin}} - \frac{M_z \sin(\theta)}{\pi t_{skin}^2 r_{tank}^2} & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (5)$$

The stress tensor depends on the angle θ . It is assumed that the sizing point of the skin will be one of three points around the tank section: $\theta = 0$, $\theta = \pi/2$ or $\theta = -\pi/2$. Only those three points are considered in the following optimization process, where the objective is to minimize the tank skin weight while respecting the Von Mises criteria on those three points.

$$\begin{aligned} & \underset{t_{skin}}{\text{minimize}} && \text{skin weight} \\ & \text{subject to} && \sigma_{VM}(0) \leq \sigma_e, \\ & && \sigma_{VM}(\pi/2) \leq \sigma_e \\ & && \sigma_{VM}(-\pi/2) \leq \sigma_e \end{aligned}$$

Where σ_{VM} is the von Mises criteria and σ_e the elastic limit of the skin material.

For the hemispherical bulkhead, only the pressure load is considered and the skin thickness $t_{bulkhead}$ is sized to withstand that load:

$$t_{bulkhead} = \max\left(\frac{\Delta P_{LL} r_{tank}}{2\sigma_e}, \frac{\Delta P_{UL} r_{tank}}{2\sigma_b}\right) \quad (6)$$

In this study a new sizing criteria is introduced and compared to the classical von Mises criteria. This new criteria applies to the strain and not to the stress. It originally comes from structural sizing with composite materials, but it is becoming more and more prevalent for metallic materials and even ceramic. Discussions with industry experts have shown that it is often used by aircraft manufacturers in their pre-sizing processes, and the regulatory authorities are currently reviewing its validity to certify aircraft. It is expressed as follows, where $\epsilon_I, \epsilon_{II}, \epsilon_{III}$ are the principal strains (eigenvalues of the strain matrix):

$$-3 * 10^{-3} \leq \epsilon_{III} \leq \epsilon_{II} \leq \epsilon_I \leq 4.5 * 10^{-3} \quad (7)$$

2.3. Stiffening structure sizing

After the preceding step, the skin thickness is fixed. It becomes then possible to determine the maximum allowable stress and shear that the skin can endure before buckling, which depend on frames and stringers spacing (cf. fig 1). As the skin should not buckle at the operational load and by making the assumption that $b = 4a$ it yields [7]:

$$\frac{\sigma_{comp,maxOL}}{\sigma_{comp,buckling}} = \frac{\frac{M_{z,OL}}{t_{skin}\pi r_{tank}}}{3.3 \frac{t_{skin}^2 E}{a^2(1-\nu^2)}} \leq 1 \quad (8)$$

$$\frac{\tau_{shear,max}}{\tau_{shear,buckling}} = \frac{\frac{T_{max,OL}}{t_{skin}\pi r_{tank}} + \frac{M_{torsion,OL}}{t_{skin}2\pi r_{tank}^2}}{4.9 \frac{t_{skin}^2 E}{a^2(1-\nu^2)}} \leq 1 \quad (9)$$

Equations 8 and 9 give a maximum stringer spacing a that must be respected to prevent buckling at the operational load. The stringer pitch is then set to this value and the frame pitch to four times that value to make sure the buckling model of each element of the stiffening structure is robust, as suggested by the asymptotic behavior of a rectangular-shaped shell in buckling when the length-to-width ratio exceeds 3 [7]. This sets the number of frames and stringers in the stiffening structure.

Above the operational load, the skin can buckle, and so it is conservatively assumed that it doesn't bear any loads anymore. But all of the skin doesn't buckle, especially around the area where the stiffeners are attached to the skin. Super stiffeners can be defined as the frames and stringers augmented with a fraction of the tank's skin, corresponding for each stiffener to an area equal to 15 times the skin's thickness in width centered around the stiffener contact point (cf. figure 4). The superstiffening structure must be able to withstand the limit load alone while remaining in elastic deformation, and it should stay below the break stress at the ultimate load.

Those constraints enable the sizing of the frames and stringers' sections. As the frames only support the circumferential stress and the stringers the longitudinal stress, for both stiffeners only the normal stress is active:

$$\sigma_{xx,super\ stringer}(\theta) = \frac{\Delta P \pi r_{tank}^2}{N_{stgr} A_{superstgr}} - \frac{M_z \sin(\theta)}{I_z} \quad (10)$$

$$\sigma_{xx,super\ frame} = \frac{\Delta P L_{tank} r_{tank}}{N_{frm} A_{superfrm}} \quad (11)$$

Where I_z is the moment of inertia, N_{frm} and N_{stgr} are the respective number of stringers and frames, and $A_{superfrm}$, $A_{superstgr}$ is the area of one super frame and one super stringer, equal to both the area of one frame or stringer plus $15t_{skin}^2$. Similarly to the sizing process of the skin, the stiffener area is found by the following optimization loop:

$$\begin{aligned} & \underset{A_{stringer}, A_{frame}}{\text{minimize}} && \text{tank weight} \\ & \text{subject to} && \sigma_{VM,LL}(\pi/2) \leq \sigma_e, \\ & && \sigma_{VM,LL}(-\pi/2) \leq \sigma_e \\ & && \sigma_{VM,UL}(\pi/2) \leq \sigma_{break} \\ & && \sigma_{VM,UL}(-\pi/2) \leq \sigma_{break} \end{aligned}$$

3. Analysis

The methodology previously presented can size a tank structure and determine its mass, which is the most important parameter at the conceptual design phase. To be truly useful, such a model must be integrated into a general multidisciplinary aircraft design analysis. The following analyses are, however, conducted with a hypothetical tank to illustrate the capability of the methodology. The results, except for some general trends, should not be taken as absolute.

The model developed was implemented in Python within the FAST-OAD framework [8]. FAST-OAD is a multidisciplinary optimization and analysis tool that is based on OpenMDAO

[9] and aims at designing an entire aircraft at the conceptual level. If the design process for the hydrogen tank doesn't constitute a fully looped analysis, it still uses a representation of the CERAS aircraft as the basis for tank sizing. The optimization problems are solved with the scipy solver "minimize" using the SLSQP method.

According to a previous study at ONERA, a typical single-aisle medium-haul aircraft without current technologies would need approximately 10 tons of hydrogen for a 2750 nm, 150-pax mission. This can be contained in a tank 10 meters in length and 3.8 meters in diameter, with hemispherical heads, representing 140 m³. The tank material is the aluminum alloy 2024, as it is lightweight, strong, and impermeable to hydrogen. A first analysis summarized in table 1 was made with a design operational pressure of 2 bar.

Table 1. Characteristics of two tanks sized with different sizing criteria

| Sizing criteria | | Von mises | Main strains bound |
|-------------------|----------------------------|-----------|--------------------|
| Stingers | Number | 71 | 217 |
| | Section (mm ²) | 140 | 46 |
| | Weight (kg) | 283 | 284 |
| Frames | Number | 15 | 46 |
| | Section (mm ²) | 1344 | 378 |
| | Weight (kg) | 686 | 593 |
| Skin | Thickness (mm) | 2.1 | 0.9 |
| | Weight (kg) | 702 | 333 |
| Bulkheads skin | Thickness (mm) | 1 | 0.9 |
| | Weight (kg) | 137 | 117 |
| Total weight (kg) | | 1807 | 1327 |
| Gravimetric index | | 0.81 | 0.85 |

It is interesting to note that the weight of the stiffening structure represents more than half of the total weight for both tanks. As could be expected, the more permissive sizing criteria on the main strain lead to a lighter tank, meaning that a validation by the certification authorities of this criteria could be really interesting for aircraft manufacturers.

The final gravimetric indexes obtained seem a little optimistic compared to previous studies, but the weight of insulation and other fuel systems like pumps, valves etc. has not been taken into account at this point.

It is also possible for the same tank to change the design operating pressure and see how its performance is evolving. Figure 5 shows that with the strain sizing criteria the weight seems to increase linearly with the operating pressure, with a gravimetric index decreasing accordingly. Figure 6 gives a little more insight on how the tank structure changes with the pressure: as it rises the number of stringers and frames decreases (by approximately 70% between 1.5 and 5 bar for both) but their sections increase (multiplied by more than 12 between 1.5 and 5 bar), resulting in an increase in weight. The weight of the frames stays, in all cases, higher than the stringers and the ratio worsens with higher pressure. This makes sense as the frames support mainly the hoop stress, which is double the longitudinal stress. The stress due to the pressure also seems to be the main driver for the stiffening structure.

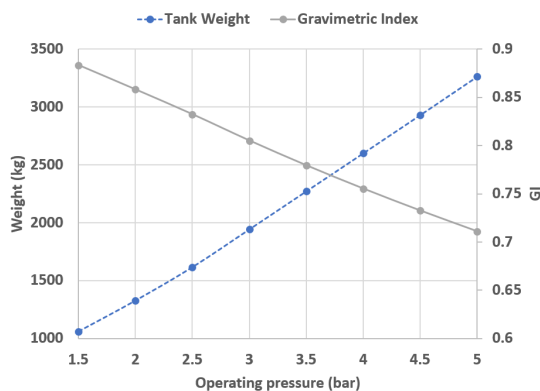


Figure 5. Evolution of tank performances with operational pressure

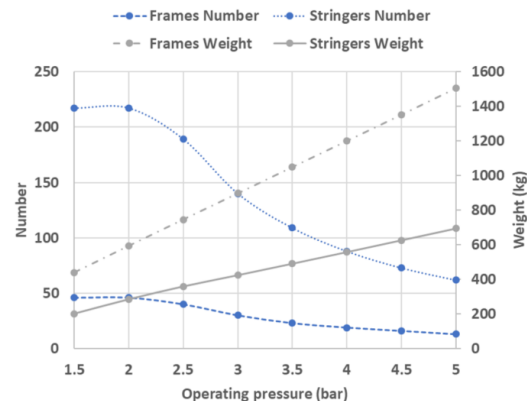


Figure 6. Evolution of tank characteristics with operational pressure

4. Conclusion

One possible way to respond to the current climate crisis for the aviation industry is through the introduction of hydrogen aircraft. Designing such aircraft means being able to size liquid hydrogen tanks, which are much bigger and heavier than their kerosene counterparts. As their design must now be included early in the aircraft design, this study presents an analytical methodology to size the structure of such hydrogen tanks. The model developed is capable of sizing a cylindrical tank with hemispherical heads of any dimensions or materials located in the back of the fuselage in a conventional aircraft configuration. By determining how much load is transmitted through its attachment points, it can model integral and non-integral solutions. It also integrates a new sizing criteria based on the main strain, which shows an increase in final performance but remains to be validated. Initial analysis conducted with the model investigated the dependency of the tank gravimetric index to the operational pressure and gave some insight on the evolution of the best stiffening structure configuration when operational pressure increases.

This work should now be completed with a thermodynamic analysis of the hydrogen tank to size the insulation and evaluate the boil-off. Another study to size the other fuel system component must also be added. It could then be integrated in a more complete multidisciplinary aircraft design analysis to estimate the performance of a potential hydrogen aircraft.

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