Progress on Advanced Cryo-Tanks Structural Design Achieved in CHATT-Project

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Abstract

The EU-FP7-funded study called CHATT (Cryogenic Hypersonic Advanced Tank Technologies) was initiated early 2012 and successfully finished in June 2015. One of its core objectives has been the investigation of Carbon Fiber Reinforced Plastic (CFRP) cryogenic pressure tanks.

The focus of the paper is on the technology development tasks of the study and its major obtained results including manufacturing and testing of four subscale tanks.

Subscripts, Abbreviations

CCTD	Composite Cryotank Technologies and Demonstration (of NASA)	MEOP	Maximum Expected Operating Pressure
CFRP	Carbon Fiber Reinforced Plastic	PE	Poly-Ethylene
CTE	Coefficient of Thermal Expansion	PP	Poly-Propylene
FEM	Finite Element Method	RT	Room Temperature
GFRP	Glass Fiber Reinforced Plastic	TPS	Thermal Protection System
LH_2	Liquid Hydrogen	TRL	Technology Readiness Level
LN_2	Liquid Nitrogen	UD	Uni-Directional

1 INTRODUCTION

In future aviation and particularly in hypersonic systems new propellants will be used, such as liquid hydrogen, liquid methane and possibly liquid oxygen. EU funded studies in Europe such as FAST20XX, ATLLAS or LAPCAT investigated advanced vehicles with these fuels for passenger transport like the SpaceLiner or Lapcat A2 and some of their constituent materials and associated propulsion challenges. The question of cryogenic propellant storage inside an airliner – although of critical importance but by far not yet mastered – had not been addressed in comparable detail until the start of the CHATT project.

The need for more detailed investigations on liquid hydrogen or methane tanks in future airliners is not only useful in future hypersonic aeronautics, but is also essential for environmental reasons in subsonic aviation. Liquid hydrogen, produced on the basis of renewable energy, is the only known new fuel meeting the requirements. Although cryogenic fuels are already operational in advanced launcher systems (e.g. Europe's Ariane rocket), an airliner will need more complex technology. New materials and design concepts are required, such as fiber based composite materials, in order to reduce the tank weight and to increase the structural performance. Different to current rocket launch systems, the durability through hundreds or even thousands of flight cycles must be assured. The propellant tank technologies are critical for the vehicle operations, cost and safety.

Meanwhile, NASA and Boeing have made significant progress in the US within the Composite Cryotank Technology Demonstration (CCTD) Project in which a large-scale composite liquid-hydrogen cryogenic tank has been designed, built and tested under relevant flight loads.

2 ORGANIZATIONAL STRUCTURE

The project CHATT has been part of the European Commission's Seventh Framework Programme and run on behalf of the Commission by DLR-SART in a multinational collaboration.

The CHATT project has been broken down into three main technical activities with close interaction. A central, steering role was applied to system requirements of advanced passenger airplanes, the development, test and implementation of engineering methods and tools. The two remaining workpackages were dedicated to fundamental research with special focus on manufacturing and testing of fully integrated subscale hardware

samples. The total budget for all activities including system analyses, fluid behaviour, and material compatibility tests was at 4.2 M€

More details of the CHATT project's organization with a list of all involved partners are provided in references [3, 4, 10, 11, 13].

2.1 CHATT Research activities

One of the core objectives was to investigate Carbon Fiber Reinforced Plastic (CFRP) cryogenic pressure tanks. Four different subscale CFRP-tanks have been designed, manufactured, and tested. The advantages and disadvantages of using liner/linerless tank designs have been investigated as well as issues related to the realization of more complex geometrical tank shapes. Major progress achieved is described in section 3.

All advanced cryogenic tank technologies to be investigated within CHATT have been driven by system demands of future hypersonic passenger configurations. Such vehicles are under study in other EU-funded cooperative projects LAPCAT and FAST20XX [3]: LAPCAT A2, LAPCAT M8, and the SpaceLiner. Thus, the vehicles have already reached a certain level of maturity in their respective propulsion demands and overall size. However, the cryogenic tank systems have not been studied in any detail and major challenges concerning tank weight, sloshing, and insulation had not been addressed prior to the start of the CHATT project.

An interesting alternative to air-breathing hypersonic passenger airliners in the field of future high-speed intercontinental passenger transport vehicles might be a rocket-propelled, suborbital craft. Such a two stage RLV has been proposed by DLR under the name SpaceLiner [1]. Ultra long-haul distances like Europe – Australia could be flown in 90 minutes. The reference configuration is the SpaceLiner 7 reached after several evolutionary steps [2, 16] is shown in Figure 1. The propellant crossfeed between the two rocket-powered stages of the SpaceLiner enables a significant performance improvement. However, crossfeed between operational stages is highly innovative and has never been demonstrated in flight. A simulation of the steady and transient behavior in the propellant feed-system has been performed along the powered flight and its preliminary design has been defined [2, 16, 17].
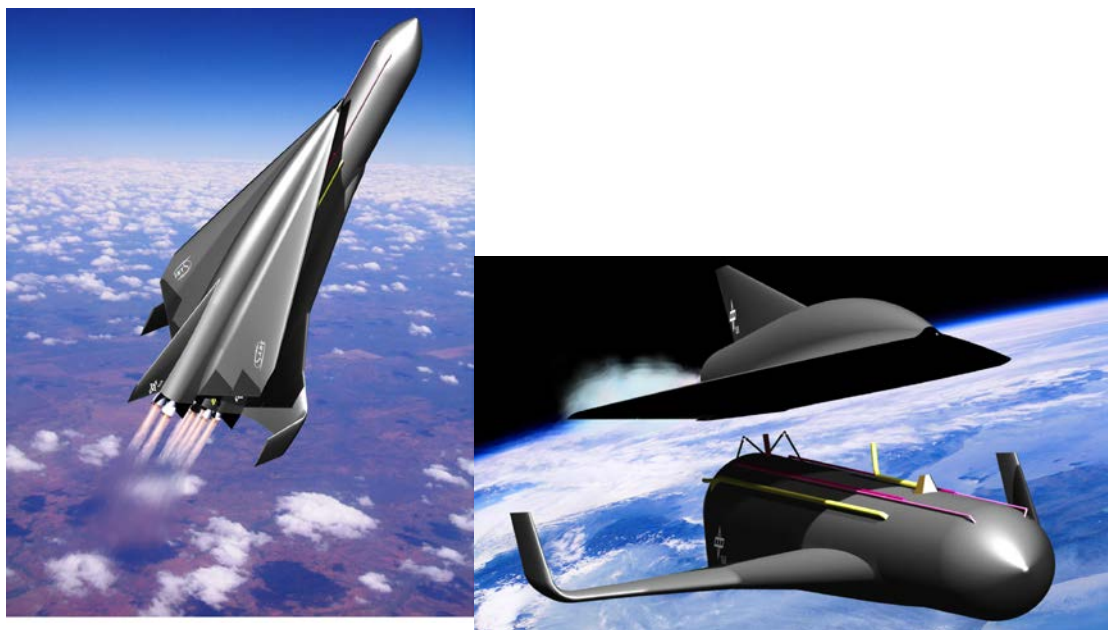

Figure 1: SpaceLiner 7 rocket-powered hypersonic passenger transport in artist's impression

Propellant management is imperative to achieve reliable and efficient vehicle operation. Therefore, this subject has been the third pillar of the CHATT study covering tank pressurization, fuel location/retention, and sloshing in horizontal tanks. Apart from thermal aspects, sloshing of cryogenic fluids within the tanks can have a significant impact on its center of gravity and hence its controllability is put into question.

Further, a ceramic heat-exchanger has been designed and manufactured in CHATT as well as the air-conditioning system for the airbreathing hypersonic vehicles. Further, a cost efficient production process has been developed for alumina cryogels, an open-celled, nanoporous, solid foam like aerogels which could become an attractive insulation material for cryogenic tanks in the future [10, 17, 18].

3 COMPOSITE CRYOGENIC TANK INVESTIGATIONS

Fiber reinforced composite materials are structurally most efficient for pressure vessels because there is the possibility to direct the right amount of fibers according to the orientation and the magnitude of the principal stresses, which makes it an iso-tensoid structure. However, some specific challenges remain with large scale cryogenic tanks of relatively low internal pressure which might require a (potentially metallic) liner and hence face difficulties beating the optimized metallic launcher tank structures. However, more advanced "linerless" CFRP-tanks are now under investigation.

3.1 Large-scale CFRP tank demonstrators in the United States

Several research programs in the US have fabricated and tested composite LH2 tanks including DC-XA (circa 1994), X-33 (c. 1999) and the Space Launch Initiative (SLI) Composite Cryotank Program (c. 2006) [8].

NASA's goal of the Composite Cryotank Technology Demonstration (CCTD) Project was to design and build a composite liquid-hydrogen cryogenic tank that can save 30% in weight and 25% in cost compared to state-of-the-art aluminum metallic cryogenic tank technology [8]. The loads, length, and volume were based on a 10 m diameter LH2 tank for an Ares V launcher Earth Departure (upper) Stage (EDS). The NASA team developed a metallic aluminum alloy cryotank concept for comparison to three industry IM7/977-2 composite concepts with the same overall dimensions: Boeing fluted core, Lockheed-Martin externally stiffened, and Northrop Grumman sandwich. All three composite concepts exceeded the 30% weight reductions desired by the CCTD Project when compared to the metallic cryotank [8].

NASA selected a 5.5-m diameter demonstrator test tank in CCTD Phase II which has been manufactured by Boeing. This tank is linerless and is using thin-plies for permeation barrier, ventable and purgeable sandwich structures, and structural Health Monitoring to support damage tolerance [5]. After initial successful completion of a 2.4 m precursor test article [5, 6], this tank has been built around a 5 m segmented tool mandrel and subsequently been tested in 2014 at NASA MSFC. The Boeing-built tank passed a series of fill-and-drain tests, containing cryogenic liquid hydrogen with acceptable seepage [7]. Weight savings over aluminum approached the 35% target set by NASA [7].

The manufactured CCTD-project-tanks used out-of-autoclave cured graphite/epoxy material and processes to enable large (up to 10-m-diameter) cryotank fabrication, and thin-ply prepreg to minimize hydrogen permeation through tank walls [9]. Both tanks were fabricated at Boeing using automated fiber placement on breakdown tooling. A fluted core skirt that efficiently carried axial loads and enabled hydrogen purging was included on the 5.5-m-diameter tank [9].

The CCTD Phase 2 project achieved its principal goal of demonstrating a 25 to 30% lower weight design traceable to an 8.4 m upper stage liquid hydrogen tank [9]. Two all-composite cryotanks were designed, built, and tested within 30 months of contract start. Both were successfully subjected to cyclic pressure testing with liquid hydrogen, and the 5.5 m cryotank was also subjected to flight loads in combination with pressure loads [9].

3.2 CFRP demonstrator tank structures in CHATT

The European technology has not yet reached the same level as recently demonstrated in the US. At least within CHATT some progress has been achieved in Europe by four different subscale demonstrator tanks for cryogenic applications which have been designed, manufactured and tested:
- Cylindrical tank with liner by DLR
- Cylindrical tank without liner by FOI/SICOMP
- Complex shape tank with liner by TU Delft
- Dry wound cylindrical tank with liner by ALE

The work conducted in CHATT contained a study of the dependency of mechanical properties of the liner materials on temperatures relevant for cryogenic fuel tank applications. In CHATT also liner materials have been studied which were adhesively bonded to a base laminate in order to evaluate the performance of different liner candidates in contact with damage in the CFRP tank wall. Results on the liner investigations have been published in [4, 17].

3.2.1 Design of cylindrical tanks with liner

3.2.1.1 Cylindrical tank with liner (DLR)

A cylindrical tank was manufactured by filament-winding at DLR in Braunschweig. Tank design follows the CFRP-net geometry. The tank is about 3 m in length with a cylindrical length of 2.4 m and a diameter of 1 m. It

has a total volume of 1.9 m³. In particular, a combination of glass fibers and CFRP was applied, whereas the CFRP was used for a second winding with larger outer diameter on top of the glass layers. Table 1 clarifies the layup scheme. The tank was manufactured with wet winding on a PE-liner. The Epoxy resin from Huntsman Araldite® LY 564 (low viscosity epoxy resin) with Aradur® 22962 (cycloaliphatic polyamine) was used. The first layer is a helix glass layer with an angle of 6.8°.

Examples from the winding process at DLR Braunschweig are shown in Figure 2 and Figure 3. The final layer is a second CFRP hoop layer visible on the right. The finished tank is finally wrapped with a peel ply (Figure 3, left). The excess resin is removed through the peel ply. Curing in the autoclave is the normal curing cycle for the resin. The autoclave curing process finalized the tank manufacturing. Afterwards the resin appears slightly gray (Figure 3, right) resulting from small micropores caused by the impregnation of the fiber material from the foam roller.

Table 1: Parameters used in the manufacturing of the DLR CFRP tank demonstrator

model	Type	layer	orientation	position	remarks
Helix winding	glass	1/2	+/- 6.8°	Complete tank	2400tex
Hoop winding	glass	3/4	0°	Cylindrical area	2400tex
Hoop winding	CFRP	5/6	0°	Cylindrical area	2400tex
Helix winding	CFRP	7/8	+/- 41.5°	Complete tank	2400tex
Hoop winding	CFRP	9/10	0°	Cylindrical area	2400tex

Figure 2: Winding of the helix CFRP layer (left) and final CFRP hoop layer (right)

Figure 3: Wrapping of the peel (left) ply and finished CFRP demonstrator tank after curing in autoclave (right)

The large cylindrical CFRP-tank was delivered in May 2014 to the cryogenic laboratory at DLR Bremen for further testing. Fill- and drain procedures using water have been run and leakage under pressurized conditions is found to be small. The sloshing and related fluid damping behavior has been tested on a hexapod table using water and is compared with CFD simulations [17]. A test with cryogenic liquid nitrogen (LN_2) had also been performed in which the tank was filled just up to the flanges' openings at the spherical end of the tank where small leakage had been detected in the pressurized water tests. In such way any cryogenic fluid spillage of the tank could be avoided. The test was intended as a pass or fail test for the structure under relevant temperature conditions of about 77 K. No pressure was applied to the CFRP tank during the test and therefore the flange openings of the tanks remained open (Figure 4). Chill-down and LN_2-filling of the CFRP tank structure to the selected fill level required about 2.5 h.

Figure 4: LN$_2$ test with cylindrical CFRP tank at DLR

Apart from the fact that no damage from the cooling down of the structure could be observed during the test, the stress impact led to cracking sounds. After the filling procedure has been completed, the LN$_2$ was allowed to boil-off while remaining inside the CFRP tank. After the CFRP tank returned to ambient temperature the visual inspection was repeated and no defects from the temperature cycle could be observed on either liner or CFRP structure.

3.2.1.2 Cylindrical tank with liner (ALE)

Beyond the wet-wound tanks, a dry filament wound cryogenic cylindrical demonstrator tank has been designed, produced by ALE in Delft and tested. This tank has a cylindrical mid-section with two isotensoid shaped ends. The tank has an approximate length of 0.57 m, a diameter of 0.29 m, and a volume of 33 l.

The liner has a cylindrical mid-section with isotensoid domes; see Figure 5 for global dimensions. The produced wall thickness is around 2 mm and has been determined iteratively using FEA. The length over diameter ratio is L/D = 2. Liners are produced using the blow molding process. Therefore, the material selected for the liner is PE because the previously foreseen Vectra LCP grade A435 [4] is not suitable for blow molding. Unfortunately, however, the CTE of PE is no longer favorable in combination with the T700 fibers due to its high value. The approximate liner mass is 0.38 kg.
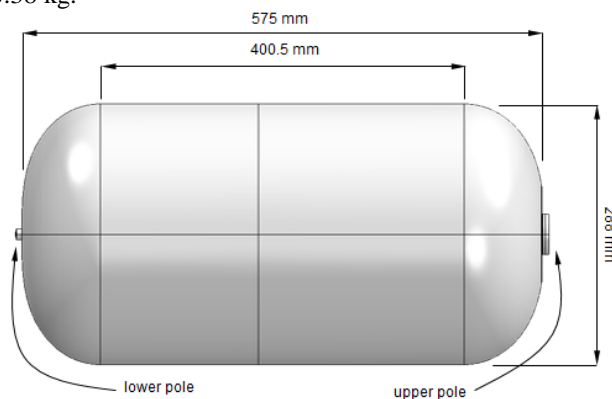

Figure 5: Liner dimensions for dry-wound tank

FEM analyses of the dry wound tank have been performed to evaluate the following aspects:
- Deformations caused by cool down from room temperature to LH$_2$ temperature
- Burst pressure validation by failure analysis of the fiber network, the liner and the closure parts at LH$_2$ temperature

The maximum fiber strain that occurs at 12 bar internal pressure (burst pressure requirement) and at LH$_2$ temperature is 0.13%. This strain magnitude is below the allowable strain of T700. With a calculated safety factor of 1.03% / 0.13% ≈ 7.9 it is concluded that the fiber network meets the load requirements.

The function of the dry carbon fiber layup is to carry the load due to the internal tank pressure. The liner and all overlying layers are assumed as non-load sharing. Toray T700 24k untwisted rovings are selected. Two different winding layers are placed in the following order:

1. Helix layer; which is a fully wrapped layer that covers the liner completely. Two T700 24k rovings are placed in 63 circuits with 8 segments filled with 8 bundles. The mass of the fibers in this layer is estimated at 0.653 kg.

2. Hoop layer; which covers the cylindrical part of the liner. The hoop layer covers the helix layer and has 108 circuits. The mass of these fibers is approximately 0.325 kg.

Winding of the helix layer and winding of the hoop layer at the ALE workshop are visible in Figure 6. Taped fiber ends and a transparent foil prevent fiber movement. A total of three tanks have been produced by ALE. The production state after winding is shown in Figure 7.
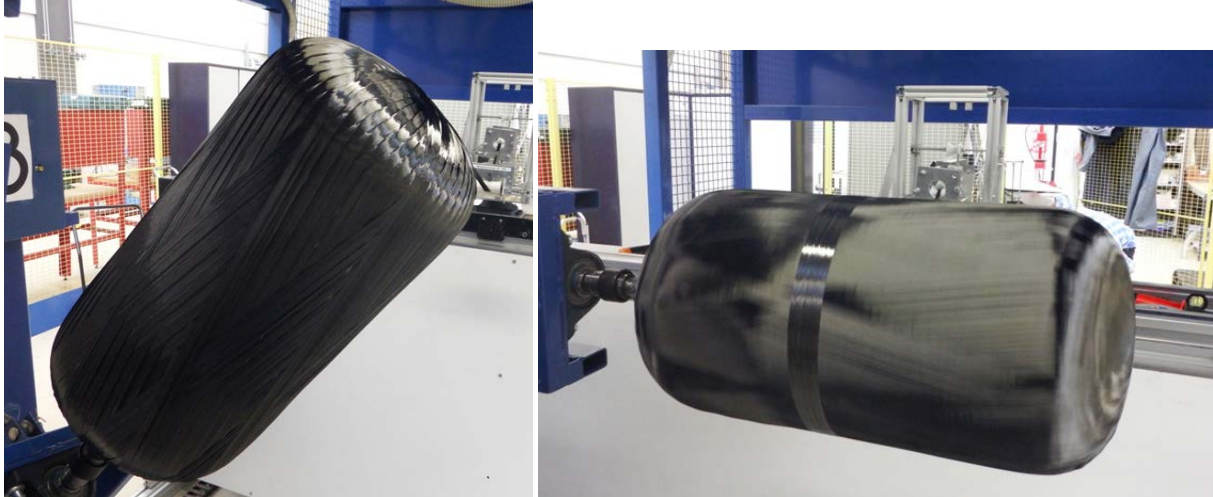

Figure 6: Winding of helix layer (left) and winding of hoop layer (right) at ALE

Figure 7: Demonstrator tank of ALE after winding with protection foil

The tank has been subject to pressurization tests at ALE and subsequently was delivered to the DLR cryolab in Bremen. Fill and drain tests using liquid nitrogen have been performed including a sequence of several pressurization and venting cycles. The main risk of using a dry filament wound tank in cryogenic environment is that in unpressurized state the fibers could separate from the liner due to the difference in their CTE and start to relocate. Actually, cooling caused the PE-liner to shrink significantly with respect to the fibers, which caused a gap (approximately 5 to 10 mm) between fibers and liner. At higher pressures the fibers would become load bearing due to expansion of the liner, provided that the liner is able to stretch far enough to close the gap without cracking. As a cautious approach, such high pressures have not been tested under cryogenic conditions for this tank in CHATT. Therefore, the actual advantage of carbon fiber reinforcement in aerospace was not demonstrated for the dry-wound tank in relevant conditions.

The ALE-tank was cooled down slowly to prevent large thermal gradients. After filling to approximately 80% volume the vessel was repeatedly pressurized by LN_2 due to boil off (Figure 8).

Twelve pressure cycles were performed in total: 1 cycle to 0.6 bar, followed by 10 cycles to 0.5 bar and finally a single cycle to 1.0 bar. No failure occurred during testing. After cryogenic filling and subsequent drying the two intact demonstrator tanks were pressurized again at room temperature to at least 12 bar to validate strength. No failure occurred during these tests.

Figure 8: LN$_2$ testing of ALE demonstrator tank

3.2.2   Design of cylindrical tanks without liner (Swerea SICOMP, FOI)

Actually, the linerless tank demonstrators built in Sweden are not closed volume tanks but rather tubes with a cylindrical section and open ends. The reason for choosing the tube configuration is the ability to validate the design by easy testing in the relevant loading conditions internal pressure, low temperatures and axial load. The manufacturing of the tube demonstrator tank is performed at Swerea SICOMP while the testing is executed at FOI. The linerless demonstrator tank concept is based on the utilization of thin-ply laminates and the superior mechanical properties these novel materials show. Both, all thin-ply tank concepts and hybrid concepts are evaluated. Several subscale demonstrator tubes were manufactured by filament winding on a steel mandrel with an external diameter of 165 mm to verify the results and test various concepts.

Numerous processing methods have been studied including one and two step winding and curing, variable winding tension, induction heating and shrink tape. However, most of the studied combinations of traditional material- and process parameters have a small effect on the operational stress state in the tank. The intended step-change in material performance was instead reached by utilizing a novel spread-tow material from the Swedish Oxeon company named TeXtreme®. As laminate material the Carbon Fiber Spread Tow TeXtreme® 50 UD TR50S WO /20:50, unidirectional, at 50 μm ply thickness has been used. Spread tow is a relatively new material and has a huge potential for performance improvements in many applications.

Finite Element analysis was used for various demonstrator cases, such as hybrid laminates (traditional and thin-ply composites) as well as pure thin-ply composites (only using TeXtreme®), to find the optimum lay-up of the demonstrator tubes considering both the real load case as well as the selected test conditions used at FOI for testing of the demonstrator tubes. Mechanical testing on specimen level performed at Swerea SICOMP also show that the critical transverse micro-crack initiation stress increases approximately from 60 to 120 MPa depending on the ply thickness

The TeXtreme® material had never been used for wet filament winding before the CHATT project started. Initial test tubes were hence manufactured by Swerea SICOMP to verify the quality of the laminates. The selected winding angle was 89.8° (tangential) with 2 mm laminate thickness. The void content in the manufactured samples were measured and found at 5%, which is unacceptably high. The problem was traced to the poor processability regarding permeability in the thickness direction.

This manufacturing problem was solved by introducing an innovative solution called HOMS (HOles, Momentary or Stationary) in the spread tow weave to facilitate impregnation [14]. The idea is to temporarily push the carbon fibers sideways in a gentle manner without damaging the fibers during manufacturing. Additional test tubes with the new method were manufactured by SICOMP using the same process parameters, lay-up and thickness as the previous test tubes including the HOMS procedure. The void content in the manufactured samples were measured and the void content was approximately 0 %, which is considered high quality manufacturing (Figure 9).
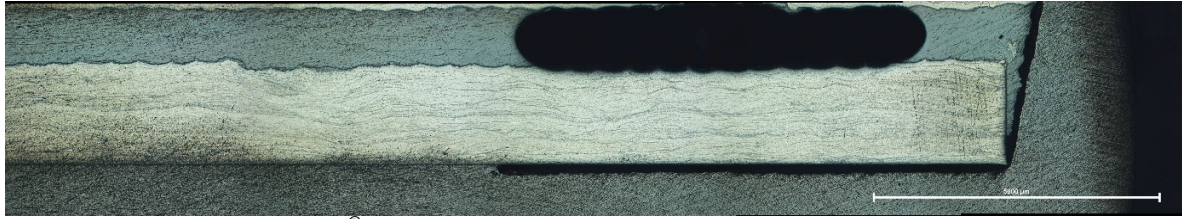
Figure 9: 2 mm thick TeXtreme® carbon/epoxy laminate with 0 % void content

Several tubes with different fiber architecture, different laminate thickness and orientation were manufactured. Some of the tubes were produced with the primary objective of optimizing the manufacturing procedure and some of them for testing at FOI in terms of performance as demonstrator "tanks".

Manufacturing of the final optimized hybrid demonstrator casing is shown in Figure 10. Four layers of traditional T700 have been wound at ±45° and 20 layers of thin-ply TeXtreme® at ±25°. The tube's ends are wound with glass fiber at 90° to serve as tabs for testing. An internal view of the finished demonstrator tube is shown in Figure 11.
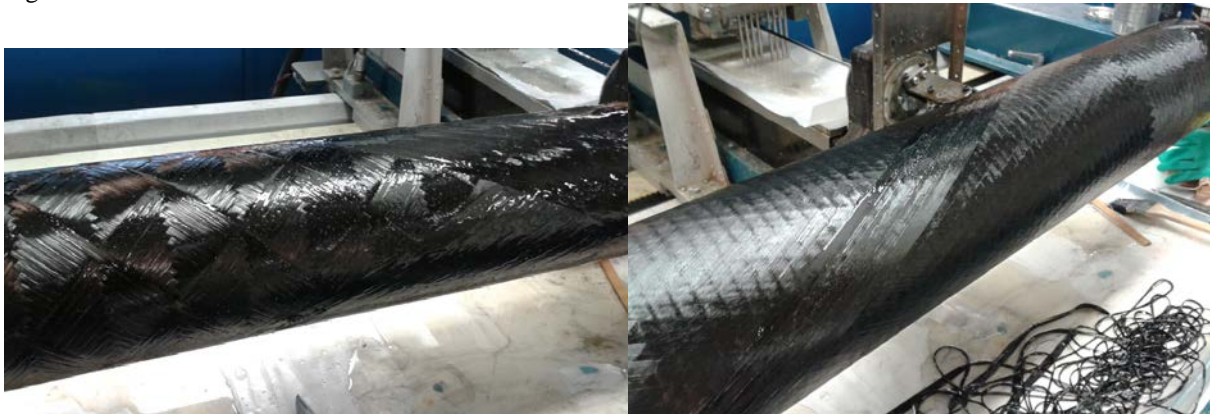

Figure 10: Tube manufacturing with ±45° layer of T700 (left), ±25° layer of TeXtreme® (right)

Figure 11: Inner surface of finished subscale demonstrator tube

The optimization of the lay-up and material in the final demonstrator tube was performed for the specific load case used at FOI: -150°C, an inner pressure of 3 bar and increasing the axial load until failure. Helium gas was used for tracing the leak rate throughout the test together with strain gauges to measure the strain at critical locations in the demonstrator. The test setup is shown in [13, 17]. Load was applied by separating the load frame grips at a constant rate of 0.5 mm/min during constant recording of force, leak rate and pressure in the vacuum jacket. The failure was obvious and catastrophic as the leak developed instantaneously saturated not only the He mass spectrometer but also the vacuum pumps resulting in a sharp increase in pressure.

After demounting of collets and vacuum jacket the tube was slightly pressurized and the leak area was identified using soapy water bubble testing. Further investigation of the failure was conducted at Swerea SICOMP with the objective to identify the failure mechanism responsible for the failure. As can be seen in Figure 12, there are multiple damages in the leak area as well as extensive amount of voids in the conventional ±55° layers.
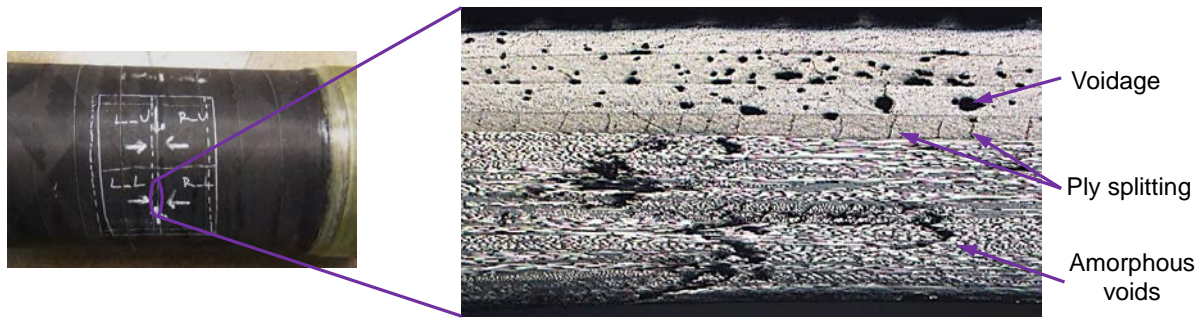
Figure 12: Microscopy of the failure locus after completed mechanical testing

The results of the mechanical testing performed at FOI validated the desired performance of the design configuration used for the linerless tank concept.

3.2.3   Design of Cryogenic Tanks with Complex Shape (TUD)

Tanks with a more complex shape than cylinders and spheres offer the potential of an improved volumetric efficiency inside the fuselage or wing of hypersonic vehicles. A relatively simple structure has been selected for the CHATT scaled prototype of a multibubble tank to be built at TU Delft which, however, contains all the specific design and manufacturing issues of such a complicated spheres arrangement. It has been decided to design, evaluate and produce a planar arrangement of identical spheres with double symmetry. The radii of the four bubbles of the intended prototype are all at the same 150 mm. The distance between the centers of the incomplete spheres is equal to $R\sqrt{2}$.

Mechanical and thermal loads are derived of the SpaceLiner (Figure 1) passenger stage LH2-tank. These are representative of hypersonic applications although a multibubble tank is unlikely to be selected in the SpaceLiner for carrying cryogenic fluids. However, water of the active cooling system could be stored very efficiently inside the available volume of the wing root using this special tank shape. The selected design configuration is a composite overwrapped subscale tank with a hoop fiber reinforcing the intersections and thus providing structural support. An external UD carbon tow (roving) is applied over the tank wall from the outside to the inside under tension, thus forming a ∞-sign (Figure 13). Each hoop fiber-wrapping cycle starts from the top section of the tank at the junction intersection and continues to the central hollow tube covering all unreinforced junctions at longitudinal and circumferential directions. Additionally, the area where the four intersections meet and the circular tube starts should have high radius of curvature, since the entrapped hoop fibers should be stretched against the tank wall surface. This way it will keep the sub-scale tank compact and provide support without adding extra weight to the tank. As a result the concept of having reinforcement webs at the liner and adding extra weight at the tank can be potentially dropped and thus maximizing the structural efficiency of the sub-scale tank by using hoop fibers
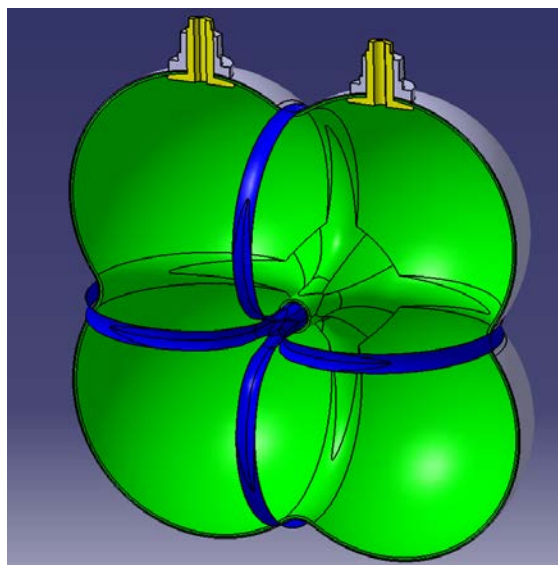

Figure 13: Intersecting spherical cells with carbon UD tows at intersections shown in blue

In a related CHATT workpackage, mixed variable optimization using two categorical variables to define the material type and bubble configuration with one continuous variable for the radius of the bubble has been carried

out by Cenaero. This approach successfully found the optimum bubble configuration for the tank with the maximum structural efficiency within the prescribed constraints [15].

The chosen liner material was polypropylene (PP) C014, with a melting point of 140°C, which is higher than the curing temperature of the composite and compatible with all roto-molding heating systems. The liner has been manufactured in a closed mold by rotation molding and the selected tank wall material is 913C carbon/epoxy. A manufacturing challenge is posed from the desired tank contour, since the fibers must be very carefully wrapped over the intersections and the central hollow tube for an effective load transfer between the laminate membrane and the tows. Additionally, filament winding is not a manufacturing process option due to the tank shape. As a result the chosen manufacturing process was hand lay-up, through draping UD-carbon patches over the liner surface. Figure 14 illustrates the process of draping UD carbon fiber patches on the liner. The layers were applied in a way that gaps between patches, which are potential weak spots, are avoided. At the poles with the metallic inserts (for filling/draining) patches at the shape of rings were added, in order to provide support to the tank near the openings. At the poles without the metallic inserts, spherical patches were employed in order to avoid triangular patches and thus short fibers that wouldn't offer any structural support.
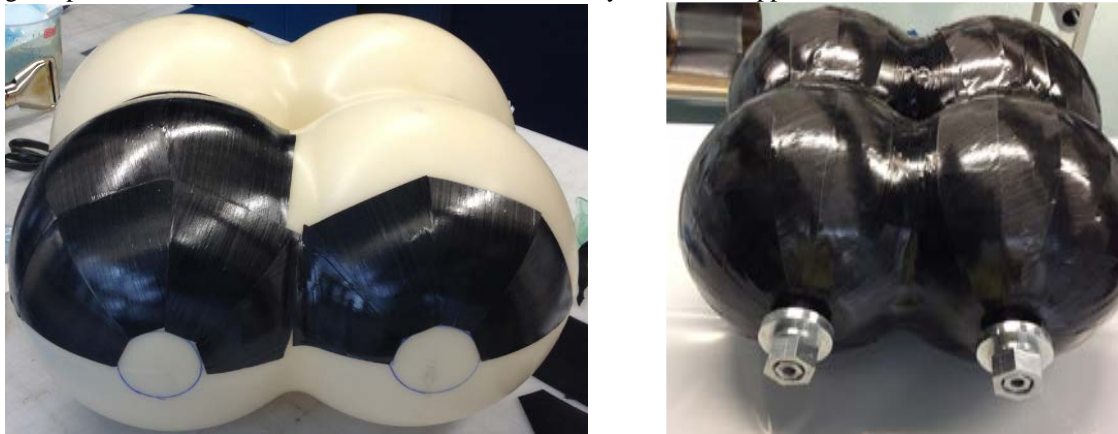

Figure 14: Draping of UD prepreg patches on the tank contour

As already mentioned, a continuous carbon roving was laid-on with tension over the different junctions, forming a ∞-symbol, like a wire that offers support at the areas, where the highest stress concentrations are expected under internal pressure (Figure 15). Figure 15b shows the top view of the respective region where the carbon rovings stretched against the liner surface meet up.
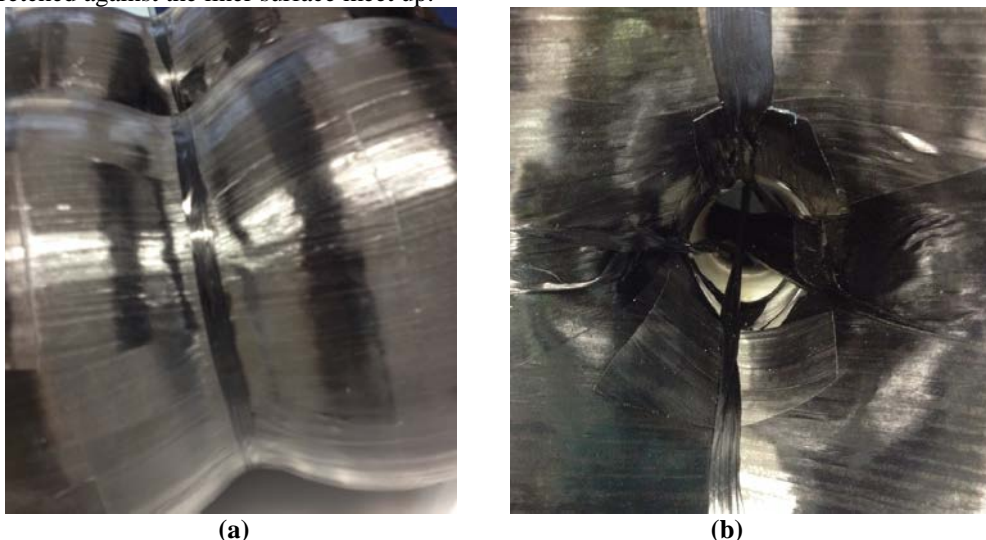

(a) (b)

Figure 15: Reinforcement of the intersections through the use of a carbon roving

After draping a peel ply was applied on top of the tank to remove excess resin during curing. Subsequently a vacuum was built up to cover the full tank and to remove all the air throughout curing. Curing time was about 300 minutes and maximum temperature reached 125°C.

A hydrostatic pressure test was performed to indicate if the manufactured tank withstands the design pressure (MEOP) of 3.8 bar. The test was carried out at the ALE facilities. Initially a leakage test had been performed indicating no leak. For the actual test the tank was filled with water. Afterwards, the pressure increase rate was

homogenized at 1 bar/min until reaching 5.1 bar, the highest internal pressure reached before damage occurred. The reinforcing fiber stretched significantly at the intersections (due to internal pressure) and thus one end debonded at the intersection between the two polar fittings, the stress was re-distributed to the already loaded adjacent fibers of nearby composite patches and some of them broke leading to some of the load being carried out by the liner locally.

As a result a small crack was formed at the liner in this region, resulting in water leakage and pressure loss. The water pressure was then forced slowly to slightly rise again, causing further crack opening and liner rupture and local fiber breakage that eventually led to tank burst. The burst is located where the two fiber-overwrap-ends meet at the intersection between the two polar openings. This leads to the conclusion that longer hoop reinforcement, covering all the intersections twice, in order to increase thickness and decrease stress at the hoop fiber- should be applied in future designs.

4   CONCLUSION

The project CHATT has been part of the European Commission's Seventh Framework Programme and was run by DLR-SART in a multinational collaboration. The project started in January 2012 and has been successfully finished as planned after 42 months in June 2015. The objectives of this effort with a total budget exceeding 4.2 M€ has been the investigation of different CFRP cryogenic pressure tanks, propellant crossfeed systems, advanced thermal insulation materials, and ceramic heat-exchangers. Four different subscale CFRP-tanks have been designed, manufactured, and tested.

The CHATT project contributed to significant progress in the design of composite tanks for cryogenic propellant applications in Europe. Previously, the FLPP program of ESA made first steps into this technology. The different subscale demonstrators built in the project allow for a reliable assessment of promising and less-promising technologies. Polymer liners seem to be feasible for short duration applications but are sensitive to cracking. A linerless tank technology as investigated by Sicomp is promising and should be further refined, introduced into complete tanks and tested in a cryogenic propellant environment. A demonstrator multi-bubble tank was manufactured by roto-molding the plastic liner (PP) and draping UD pre-impregnated carbon/epoxy patches over the liner surface area and overwrapping the junctions with a carbon roving. The tank was tested under hydrostatic pressure up to a MEOP safety factor of 1.35 when failure occurred. The failure-pattern was associated with hoop overwrap debonding from the tank and resulting stress-re-distribution, which led to fiber breakage at the patches and liner rupture that caused a tank burst.

In future projects the lessons learned of CHATT will be useful to bring European composite tank technologies forward. Currently, the European TRL of such cryotanks is still in the range between 3 and 4 while the TRL in the US is considerably more advanced, already approaching full launcher scale dimensions with ground tests run using liquid hydrogen fuel. The next step in the development of a European composite cryotank should focus on a single, fully integrated tank demonstrator including thermal protection and some health monitoring equipment to be tested with LH_2 in multiple cycles.

5   ACKNOWLEDGEMENTS

6   REFERENCES

1. Sippel, M.: Promising roadmap alternatives for the SpaceLiner, Acta Astronautica, Vol. 66, Iss. 11-12, (2010)

2. Sippel, M.; Schwanekamp, T.; Trivailo, O.; Kopp, A.; Bauer, C.; Garbers, N.: SpaceLiner Technical Progress and Mission Definition, AIAA 2015-3582, 20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Glasgow, July 2015

3. Sippel, M.; Votta, R.; Haya-Ramos, R.: Advanced Launcher Technology Maturation Supported by EU-Aeronautic Research Projects, IAC-12-D2.5.6, Naples, October 2012

4. Sippel, M.; Kopp, A.; Mattsson, D.; Fraters, A.; Koussios, S.: Advanced Cryo-Tanks Structural Design Investigated in CHATT, SSMET2014, Braunschweig, April 2014

5. Vickers, J.: Composite Cryotank Project, Structures for Launch Vehicles, presentation at Composites Australia Conference, March 5, 2013

6. McCarville, D.A.; Guzman, J.C.; Sweetin, J.L.; Jackson, J.R.; Pelham, L.; Steensland, J.; Soden, M.B.; Petersen, C.W.: Manufacturing Overview of a 2.4 Meter (7.9 Foot) Composite Cryotank, SAMPE Journal, Vol. 49, No.5, September/October 2013

7. Morring, F.: Advances In Lightweight Composite Tanks For Launchers, Aviation Week & Space Technology, http://aviationweek.com/space/advances-lightweight-composite-tanks-launchers, May 13, 2015

8. Johnson, Th. F.; Sleight, D. W.; Martin, R. A.: STRUCTURES AND DESIGN PHASE I SUMMARY FOR THE NASA COMPOSITE CRYOTANK TECHNOLOGY DEMONSTRATION PROJECT, AIAA2013-1825, 2013

9. Jackson, J.R.; Vickers, J.; Fikes, J.: COMPOSITE CRYOTANK TECHNOLOGIES AND DEVELOPMENT 2.4 AND 5.5M OUT OF AUTOCLAVE TANK TEST RESULTS, 2015

10. Sippel, M.; Kopp, A.; Sinko, K.; Mattsson, D.: Advanced Hypersonic Cryo-Tanks Research in CHATT, AIAA2012-5945, 18th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Tours, September 2012

11. Sippel, M.; Kopp, A.; Mattsson, D.; Fraters, A.; Koussios, S.: Advanced Cryo-Tanks Research in CHATT, 5TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS) 2013, Munich, July 2013

12. Koppert, J.J.M.; de Boer, H.; Weustink, A.P.D.; Beukers, A.; Bersee, H.E.N.: Virtual testing of dry filament wound thick walled pressure vessels, in 16th International Conference on Composite Materials, 2007

13. Sippel, M.; Kopp, A.; Mattsson, D.; Freund, J.; Tapeinos, I.; Koussios, S.: Final Results of Advanced Cryo-Tanks Research Project CHATT, 6TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS) 2015, Krakow, July 2015

14. Olofsson, K. et al.: MANUFACTURE WITH SPREAD TOW FIBER MATERIALS FOR REDUCED MICRO-CRACKING, 20th International Conference on Composite Materials, Copenhagen, 19-24th July 2015

15. Mahajan, A.; Madhavan, V.; Beauthier, C.; Lonfils, T. Tapeinos, I.; Koussios, S.: High-fidelity multi-sphere hypersonic vehicle cryogenic tank design by mixed-variable surrogate-based optimization methods, 6th EUROPEAN CONFERENCE FOR AEROSPACE SCIENCES (EUCASS), Krakow, June 2015

16. Sippel, M.; Trivailo, O.; Bussler, L.; Lipp, S.; Valluchi, C., Kaltenhäuser, S.; Molina, R.: Evolution of the SpaceLiner towards a Reusable TSTO-Launcher, IAC-16-D2.4.03, 67th International Astronautical Congress, Guadalajara, Mexico, September 2016

17. Sippel, M. et al.: CHATT, PROJECT FINAL REPORT, issue1, revision 1, SART TN001/2016, 2016

18. Sinkó, K.; Kobzi, B.; Sinclaire, J.; Baris, A.; Temesi, O.: Influence of cryogenic drying conditions on hierarchical porous structure of aluminum oxide systems, in Microporous and Meso-porous Materials 218 (2015)

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