

Advanced Cryo-Tanks Structural Design Investigated in CHATT

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Abstract

An EU-funded study called CHATT (Cryogenic Hypersonic Advanced Tank Technologies) has been initiated early 2012 and recently passed its mid-term milestone. The project CHATT is part of the European Commission's Seventh Framework Programme and run on behalf of the Commission by DLR-SART in a multinational collaboration. One of the core objectives is to investigate Carbon Fiber Reinforced Plastic (CFRP) cryogenic pressure tanks. Four different subscale CFRP-tanks are planned to be designed, manufactured, and tested.

The paper outlines the study logic of CHATT, gives a presentation of the technology development tasks, and summarizes available research results on the liner testing and CFRP-tank manufacturing.

Subscripts, Abbreviations

CAD	Computer Aided Design
CFRP	Carbon Fibre Reinforced Plastic
CTE	Coefficient of Thermal Expansion
FEM	Finite Element Method
FEP	Fluorinated Ethylene Propylene
GFRP	Glass Fibre Reinforced Plastic
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
PFA	PerFluoroAlkoxy
RT	Room Temperature
SME	Small Medium Enterprise
TPS	Thermal Protection System
TRL	Technology Readiness Level
-C	cementable

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 investigate 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 – has 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 urgent 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. Cryogenic fuel propulsion is already operational in advanced launcher systems and Europe has some expertise with the Ariane rocket. However, the airliner systems will require more complex technology (compared to those existing in today's launchers), such as ultra-light-weight and reusable propellant tank systems. The propellant tank technologies are critical for the vehicle operations, cost and safety.

New materials and design concepts are required, such as fibre composites, in order to reduce the tank weight and to increase the structural performance. This is particularly important if the tank has load carrying functions. Different to current rocket launch systems, the durability through hundreds or even thousands of flight cycles must be assured. Tank liners are another essential element of a tank design in order to assure the material compatibility over long durations.

2 ORGANIZATIONAL STRUCTURE

The project CHATT is part of the European Commission's Seventh Framework Programme (FP7) and run on behalf of the Commission by DLR-SART in a multinational collaboration. One of the core objectives is to investigate Carbon Fibre Reinforced Plastic (CFRP) cryogenic pressure tanks. Four different subscale CFRP-tanks are planned to be designed, manufactured, and tested. The total budget is exceeding 4.2 M€ with an EU contribution of almost 3.3 M€ [1]. The project started in January 2012 and runs for 42 months with a scheduled end in June 2015.

Eleven different partners from seven European countries are participating in CHATT. A list of all involved partners with their country of origin and full organization name is presented in Table 1.

The organizational breakdown of the CHATT project is very balanced concerning the type of the partners and is as follows:

SME: 5 (ORB, ECM, CENAERO, GDL, ALE)

Research institutes: 3 (DLR, FOI, SICOMP)

Universities: 3 (ULB, ELTE, TUD)

Large industrial companies are not involved in CHATT. All partners receive a 75 % funding by the EU-commission for their research activities. 25 % are funded by internal contribution of each partner. The financial breakdown per country is shown in Figure 1.

The project is managed by DLR-SART with the support of Work-Package leaders based in partner organizations. Regular meetings are essential for the technical

exchange. A total of 6 progress meeting (PM) are planned (every 6-8 months) with the first three PMs held in Budapest, Piteå (Sweden), and Braunschweig. Other meetings or reviews on WP level are organized when necessary.

Table 1: List of CHATT partners

Short Name	Country	Participant organization name
DLR	Germany	Deutsches Zentrum für Luft- und Raumfahrt
FOI	Sweden	Totalförsvarets Forskningsinstitut
SICOMP	Sweden	Swerea SICOMP
ULB	Belgium	Université Libre de Bruxelles
ORB	Austria	Orbpace
ELTE	Hungary	Loránd Eötvös University (ELTE) Budapest
TUD	Netherlands	Technical University Delft
ECM	Germany	Engineered Ceramic Materials GmbH
CENAERO	Belgium	Centre de Recherche en Aéronautique ASBL
GDL	UK	Gas-Dynamics Limited
ALE	Netherlands	Advanced Lightweight Engineering

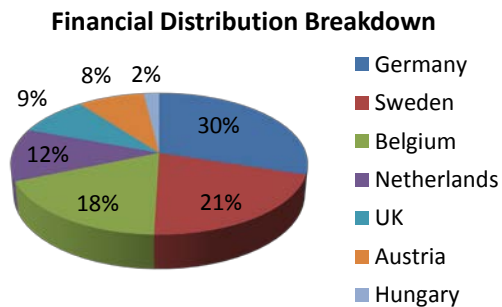


Figure 1: Financial Distribution Breakdown in CHATT per country

A dedicated public internet site featuring general information about CHATT as well as providing all published papers for download is also available at <http://www.chatt.aero>.

3 RESEARCH ACTIVITIES

The intended research in CHATT will increase the knowledge within Europe to a practical cryogenic tank demonstrator level for future aerospace reusable lightweight composite cryogenic structures. The advantages and disadvantages of using liner/linerless tank designs will be investigated as well as issues related to the realization of more complex geometrical tank shapes.

The project is broken down into three main technical activities (Workpackages WP2 to WP4), which have a close interaction as shown in Figure 2.

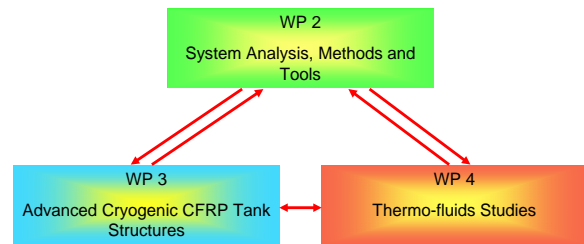


Figure 2: Interaction of different workpackages in CHATT study [1]

A central, steering role is applied to WP2 focusing on system requirements of advanced passenger airplanes, the development, test and implementation of engineering methods and tools. The two remaining workpackages WP3 and WP4 are dedicated to fundamental research with special focus on manufacturing and testing of fully integrated subscale hardware samples. Both WPs are serving as modules supporting the vehicle design and the verification of fast engineering methods.

Four different subscale CFRP-tanks are planned to be designed, manufactured, and tested under mechanical and thermal loads within the scope of the CHATT project. The challenge in developing a cryogenic CFRP tank is finding a solution for the problems caused by differences in thermal expansion coefficients (CTE) on a microscopic scale. If a liner is required, there is also the challenge to overcome the differences in CTE of the liner with respect to the structural shell.

All advanced cryogenic tank technologies to be investigated within CHATT are driven by system demands of future hypersonic passenger configurations. Such vehicles are under study in other EU-funded cooperative projects LAPCAT and FAST20XX [5]: 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 have not been addressed much prior to the start of the CHATT project.

One supersonic airbreathing vehicle being researched as part of CHATT is the A2 Mach 5 civil transport of Reaction Engines Limited. 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 [2]. Ultra long-haul distances like Europe – Australia could be flown in 90 minutes. The latest reference configuration is the SpaceLiner 7 reached after several evolutionary steps [4] is shown in Figure 3. 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 [4, 6].

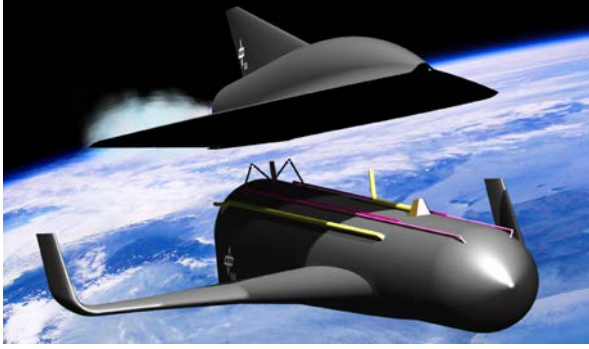


Figure 3: SpaceLiner 7 rocket-powered hypersonic passenger transport in artist's impression

Propellant management is imperative to achieve reliable and efficient vehicle operation. It is therefore the third pillar of the CHATT study and covers 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. Counter-measures such as anti-sloshing devices and tank design are susceptible to reduce these effects but will come at the cost of increased mass and production effort.

Further, a ceramic heat-exchanger will be built and tested in CHATT as well as the air-conditioning system for the airbreathing hypersonic vehicles. The aerogel is an open-celled, nanoporous, solid foam which could become an attractive insulation material for cryogenic tanks in the future. Supported by CHATT, a cost efficient production process is developed for alumina cryogels by ELTE [9].

4 STRUCTURAL TANK INVESTIGATIONS

After the CHATT-study passing its mid-term milestone, hardware manufacturing is underway and some component tests have been performed. The following sections give an overview on latest work focused on the CFRP tank studies of WP3.

Fibre reinforced 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. Carbon fibers are currently known to have the highest combination of specific strength and stiffness [3, 9]. However, some specific challenges remain with large scale cryogenic tanks of relatively low internal pressure which usually require a (potentially metallic) liner and hence face difficulties beating the optimized metallic launcher tank structures.

1.1 Assessment of suitable liners

Within CHATT several liner materials have been identified as potential polymer candidates for evaluation. It is essential that these materials have a large strain to failure at cryogenic temperature and it is necessary to match their CTE to the laminate to decrease thermal stresses. The selected liner materials for evaluation are presented in Table 2.

Table 2: Polymer liner candidates [7]

Material	Description	Notation
Vectra LCP A950	Ticona Vectra [®] liquid crystal polymer, unreinforced	A950
Vectra LCP A115	Ticona Vectra [®] liquid crystal polymer with short glass fiber reinforcement, fiber weight fraction $w_f = 15\%$	A115
Vectra LCP A130	Ticona Vectra [®] liquid crystal polymer with short glass fiber reinforcement, fiber weight fraction $w_f = 30\%$	A130
DuPont [™] FEP	DuPont [™] Teflon [®] FEP, a fluorinated ethylene propylene resin film	FEP
FEP	Hexafluoropropylene, tetrafluoroethylene	FEP_B
DuPont [™] PFA	DuPont [™] Teflon [®] PFA, a perfluoroalkoxy copolymer resin film	PFA
PFA	Perfluoroalkoxy (Teflon PFA 951HP Plus)	PFA_951
DCPD	Dicyclopentadiene (Telene 1610/1650)	DCPD_T
DCPD	Dicyclopentadiene ,reinforced (Telene 1690)	DCPD_R
PET	Polyethylene Terephthalate (Unreinforced)	PET_U
PET	Polyethylene Terephthalate (Reinforced 20%)	PET_R

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. Tensile test results typically indicate that fluoropolymer materials have a failure strain of several 100% in RT and 3% even at -150°C , while the maximum failure strain for liquid crystal polymers was around 6% at RT and less than 1% at -150°C . Hence, a comparison between different materials show that liquid crystal polymer materials (Vectra LCP A950, A115 and A130) are far less ductile than the fluoropolymer materials (DuPont[™] FEP and PFA). The results of the tensile test are visible in Figure 4

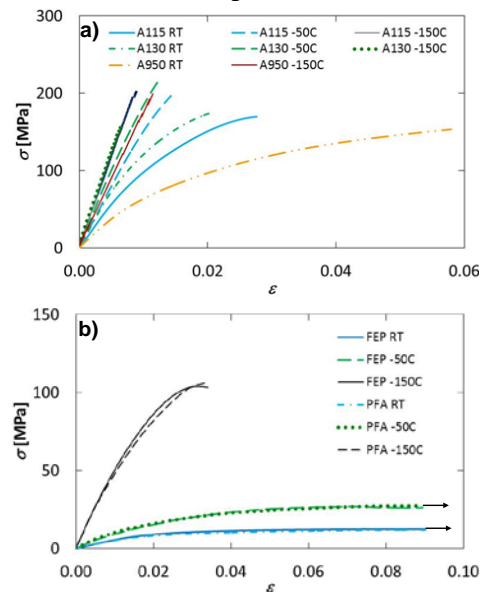


Figure 4: Typical stress-strain curves at room temperature (RT), -50°C and -150°C for a) Ticona Vectra A950, A115 and A130; b) DuPont[™] FEP and DuPont[™] PFA [7, 8]

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. The evaluation was conducted using 4-point bending tests. At -150°C , all the studied liner materials were prone to cracking due to increased brittleness. [9]

1.2 CFRP demonstrator tank structures

Four different subscale demonstrator tanks have been designed, are manufactured and will be tested within CHATT:

- 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

A cylindrical tank with ≈ 3 m overall length and ≈ 1 m diameter is currently manufactured by filament-winding at DLR in Braunschweig. The CAD-model of the planned tank is shown in Figure 5.

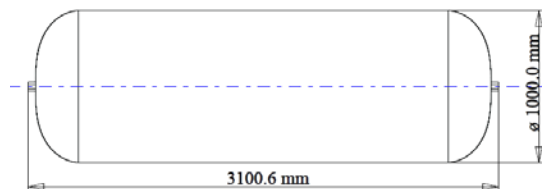


Figure 5: CAD-model of planned DLR CFRP test tank

The tank basis consists of two metal domes and a PE-Liner built in rotation moulding process. The metal domes are glued to the PE-Liner with Adekit A310/400 from Axson. The feather keys are used as an anti-rotation device.

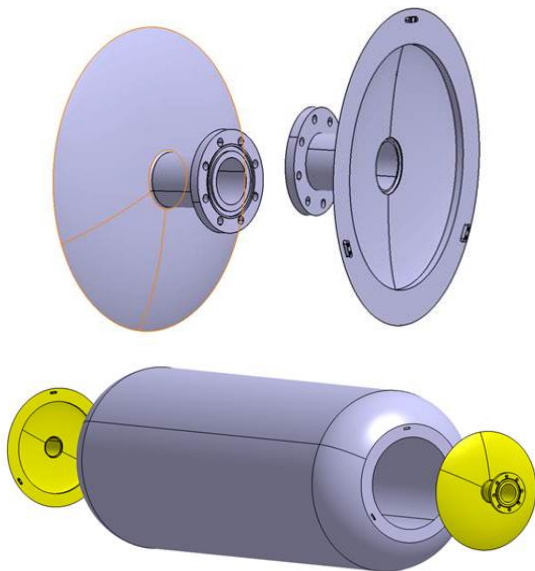


Figure 6: Metal dome and flange design and assembly with liner prior to winding

The metal domes are made of stainless steel 1.4571. It is based on AD2000 W10 with an operating temperature up to -270°C . Each dome has a weight of ~ 38 kg. The flange-pipe has an inner diameter of 100 mm. The outer diameter of the pipe is 116 mm. The pipe length is ~ 150 mm. The flange is designed to DIN EN 1092-1 PN16 DN100 Type 01 – D. The pipe stub and the flange are

made out of a rotary part. The pipe socket is welded to the contour. The contour outer diameter is 644 mm and the contour is 50 mm in height.

The first 3 m tank has been produced by the end of March after some design adaptations of the metallic flanges were found necessary during manufacturing.

The work performed by Swerea SICOMP is focused on studying potential liner-less tank concepts, materials and theoretical designs to be further evaluated. Several material combinations have been studied using 4 (2 PAN and 2 pitch) carbon fiber types, 3 epoxy types and CNT modified epoxy together with various lay-ups. Several processing methods have been studied including one - and two step winding + 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.

Therefore, a novel spread-tow material from the Swedish Oxeon company is intended to be used in the liner less tank concept. Initial mechanical testing performed at Swerea SICOMP show that the strength of the Oxeon spread-tow is dependent on the ply thickness. Hence, the critical transverse micro-crack initiation stress increases approximately from 60 to 120 MPa with these new materials depending on the ply thickness. This is probably the crucial new material needed to manufacture improved liner less tanks. Work on a similar idea by The Boeing Co. has recently been published [13].

Initial tensile tests show very good results, see Figure 7. The sample has been tested to 1.3 % tensile strain (correspond roughly to 120 MPa) with two visible micro cracks in the outer layer. It should be noted that the outer layer thickness is 2 times thicker in this sample compared to the layers inside the laminate. Even larger micro crack strains are hence possible with an optimized layup (even thinner layers, half the layer thickness on the outermost layer and tailored thickness towards the coating). A conventional $[0^{\circ}/90^{\circ}]$ carbon/epoxy roving laminate typically has 60 MPa in mechanical micro crack initiation stress in 1-D tensile testing. The corresponding value here is around 120 MPa which is an improvement by a factor of 2. This material- and layup concept are currently applied to the filament wound process used at Swerea SICOMP.

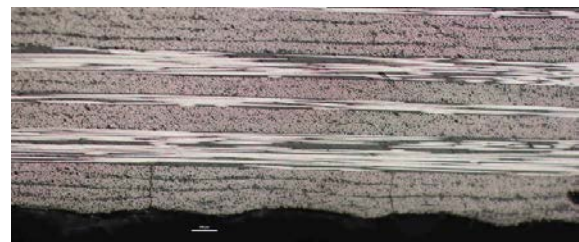


Figure 7: SICOMP manufactured $0^{\circ}/90^{\circ}$ laminate with ultra-thin layers, 0.046 mm laminate thickness

No separate liner is used in this concept. An inner coating of an ultra-high strain to failure material is however possible. The coating is expected to work better in combination with spread-tow laminate materials, due to the much smaller micro-cracking crack size which

leads to smaller local strains for the coating to handle. The inner laminate thickness (and hence the crack size) at the coating surface will be tuned in to fit the strain to breakage of the coating, in further studies.

Manufacturing of the liner-less demonstrator tanks will start in the spring of 2014.

Beyond the wet-wound tanks, a dry filament wound cryogenic cylindrical demonstrator tank will also be designed, produced and tested by ALE. 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. This tank has a cylindrical mid-section with two isotenoid shaped ends. The tank has an approximate length of 0.57 m, a diameter of 0.29 m, and a volume of 33 l. [11]

The most important requirement for the demonstrator tank is that it should have a minimum burst pressure of 12 bar during operations with liquid hydrogen. Vectra LCP A435 has been chosen as liner material and will be reinforced with dry wound T700 carbon fiber. The torque-free aluminum insert will contain the liquid hydrogen compatible Astra Seal O-ring. A polyurethane coating can be applied to the outside of the tank to protect the fibers. The design is made with the ALE in-house developed program PresVes, the CAD software SolidWorks and the FEA software Abaqus [12].

The preliminary design of the demonstrator tank using dry filament winding is shown in Figure 8. The individual fibers, modeled as Truss Elements, for both the helical and hoop layer can clearly be seen. The fiber pattern (8 segments, 8 bundles) can also be identified.

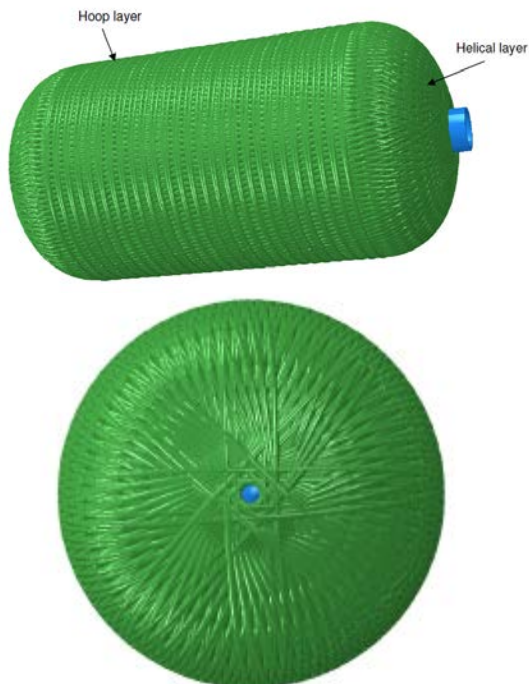


Figure 8: Preliminary design of dry wound cryogenic tank in Abaqus/CAE [11]

Tanks with a more complex shape than cylinders and spheres offer the potential of an improved volumetric

efficiency inside the fuselage of hypersonic vehicles and are, hence, included in CHATT. The simplest possible structure should be 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 therefore been decided to design, evaluate and produce a planar arrangement of identical spheres with double symmetry as presented in Figure 9. The spheres of the multi-sphere are structurally efficient shell-structures with respect to balancing the pressurization loads. Membrane forces for the sphere are given by the circumferential force.

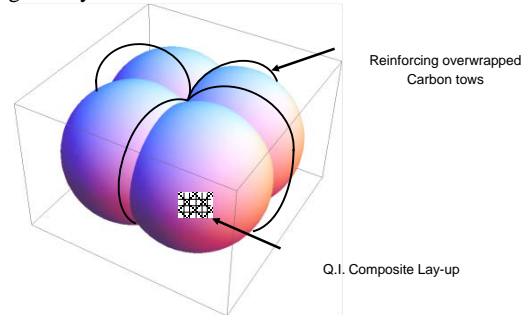


Figure 9: Arrangement of four identical intersecting spheres possessing double symmetry lay-up and external reinforcement of the multi bubble design

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 $R\sqrt{2}$. The liner is planned to be made in a closed mould by rotation moulding and has a thickness of 3 to 5 mm. Most probably, the liner material will be a liquid crystal polymer to satisfy the requirements of low permeability, resistance to cryogenic temperatures, reduced CTE mismatch, and absence of micro-cracking. At the point where the bubbles meet, the liner possesses a tube-like passage to provide space for the externally overwrapped carbon tows to go through. The liner is overwrapped by cross ply woven fabrics [90/0], that are stacked under an angle of 45° with respect to each other. By this way of stacking, a quasi-isotropic laminate can be created. In a next step the liner, which is now covered by the stacked fabrics, is packed into a bleeder foil and a vacuum foil. The resin is inserted by the vacuum infusion technique. Post processing in an oven or autoclave is necessary to remove any remaining voids and ensure complete curing of the resin. The resin is not determined yet but possibly will be a toughened epoxy.

Theoretical design drafts of a quadri-spherical bubble tank are performed to study forces and loads developed throughout the geometry and to be used for the demonstration of cryogenic fibre placed multi-bubble tanks.

A conformal (multibubble/multilobe) tank generator is being developed based on Excel. The outcome of this generator is basically a CAD design (based on CATIA), that will enable the tank visualization (example in Figure 10) as well as the calculation of the total internal volume and the calculation of the total surface area of the conformal tank. The generated CAD designs of conformal tanks will be used for static FEM analysis in order to perform a structural analysis for several defined load cases.

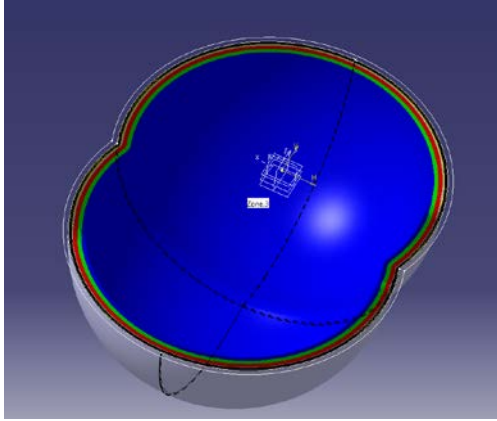


Figure 10: Visualization of multibubble tank with two cells, with centroids in the same plane

5 CONCLUSION

The project CHATT is part of the European Commission's Seventh Framework Programme and is coordinated by DLR-SART in a multinational collaboration. The project started in January 2012 and is running for 42 months with a scheduled end in June 2015. The objectives of this effort with a total budget exceeding 4.2 M€ are to investigate different CFRP cryogenic pressure tanks, propellant crossfeed systems, advanced thermal insulation materials, and ceramic heat-exchangers. Four different subscale CFRP-tanks are currently designed, manufactured, and will be tested.

Five different polymer materials were considered and analyzed for possible application as liners in cryogenic fuel tanks. Tests were run at room temperature and at -150°C. At low temperatures and under bending loads some micro-cracking reaching into the liner material was observed.

Design of the different subscale demonstrator tanks is advancing and manufacturing of some tanks is under way. Testing under pressure for potential leaking and subsequently under relevant cryogenic conditions should start later this year.

6 ACKNOWLEDGEMENTS

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Further updated information concerning the SART space transportation concepts is available at:

<http://www.dlr.de/SART>