ENHANCEMENTS OF THE DLR TOOL PANDORA FOR AUTOMATED DETAILED PRELIMINARY DESIGN AND CRASH ANALYSES

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Abstract

The DLR Institute of Structures and Design (BT) in Stuttgart has been developing the tool PANDORA (Parametric Numerical Design and Optimization Routines for Aircraft) [1] in Python since 2016, initially designed for aircraft fuselage preliminary sizing and mass estimation in process chains and parameter studies using the Finite Element Method (FEM). The development of new propulsion concepts with hydrogen or battery systems with different structural loading compared to traditional kerosene systems can only be partially represented in the preliminary design using conventional methods. In addition to quasi-static flight and ground load cases, dynamic crash load cases have also to be considered to ensure equivalent safety standards of new concepts. In first versions of PANDORA, the modeling was focused on GFEM (global FEM) models for static analyses. The GFEM base model uses a regular surface grid with simple reinforcements like frames and stringers as beam elements. This approach is fast to analyze multiple different concepts but limited to a specific range of parameters and predefined structural layouts. In a further development step, local model refinements using mesh-based approaches such as element splitting and extrusion of previously defined cross sections were implemented to allow for the first generation of DFEM (detailed FEM) models for transient crash and ditching analyzes [2]. To overcome limitations of the mesh based DFEM generation and to increase the range of fully automated and parametrized models in the preliminary design phase to be analyzed, PANDORA has recently been extended with an interface to Open Cascade (OCC) to offer versatile geometry usage. This enables geometry-based modeling and subsequent meshing (e.g. with GMSH) to analyze a wide range of concepts with more details resulting in PANDORA as a general environment for any kind of modeling. This approach is described in the first part of this paper. At DLR the specific aircraft parameters are defined in the xml based CPACS format (Common Parametric Aircraft Configuration Schema) [3] which allows interdisciplinary exchange of aircraft configurations. Based on these specific parameters PANDORA automatically creates a detailed geometry-based parametric description of the configuration which can be modified or extended and finally be used to build the FE model. This approach is exemplarily used to model double shell LH2 tanks incl. their connection to the fuselage primary structure and filling with SPH particles for subsequent sloshing analyzes (proposed paper [4]). In the second part of the paper the analysis of static flight and ground loadcases in combination with tank integration concepts is presented.

Keywords

Predesign; Geometry; CPACS

NOMENCLATURE

Technical Terms

FATIGUE	Weakening of a material caused by repeated load cycles.
CROSSBEAM	Structural member giving lateral support to the fuselage.
FRAME	Circumferential structural ring providing shape and strength to the fuselage.
GMSH	An open source 3D finite element mesh generator.
PYTHON	Free programming language.
SIZING	FEM based adjustment of thicknesses for mass estimation.
STRINGER	Longitudinal stiffener running along the fuselage to support bending loads.

Paper Specific Abbreviations

1T_M0	GFEM concept with simplified 1 tank loading.
1T_M1	DFEM concept with 1 tank and dome spokes and central z-rods.
1T_M2	DFEM concept with 1 tank and frame spokes and central z-rods.
1T_M3	DFEM concept with 1 tank and crossbeam spokes and central z-rods.
1T_M4	DFEM concept with 1 tank and dome spokes with angular offset (no z-rods).
1T_M5	DFEM concept with 1 tank and dome spokes with angular offset (no z-rods).
1T_M6	DFEM concept with 1 tank and dome spokes and z-rods at domes and center.
2T_M0	GFEM concept with simplified 2 tanks loading.
2T_M1	DFEM concept with 2 tanks and dome spokes and central z-rods.
2T_M2	DFEM concept with 2 tanks and frame spokes and central z-rods.

2T_M3 DFEM concept with 2 tanks and crossbeam spokes and central z-rods.

2T_M4 DFEM concept with 2 tanks and dome spokes with angular offset (no z-rods).

2T_M5 DFEM concept with 2 tanks and dome spokes with angular offset (no z-rods).

2T_M6 DFEM concept with 2 tanks and dome spokes and z-rods at domes and center.

Abbreviations

APDL Ansys Parametric Design Language

API Application Programming Interface

BT DLR Institute of Structures and Design

CPACS Common Parametric Aircraft Configuration Schema (.xml)

DFEM Detailed Finite Element Model

DLR German Aerospace Center

GFEM Global Finite Element Model

GI Gravimetric Index (ratio of stored LH_2 mass to total tank system mass)

LH_2 Liquid Hydrogen

MDO Multidisciplinary Design Optimization

OCC Open Cascade (open-source full-scale 3D geometry library)

PANDORA Parametric Numerical Design and Optimization Routines for Aircraft

RBE3 Distributed Constraint Element

uID Unique Identifier (for example used in CPACS to reference an object)

1. INTRODUCTION

The shift towards hydrogen and battery-electric propulsion introduces new structural challenges compared to conventional kerosene-based systems. Mass distribution, load cases, and integration of energy storage systems such as liquid hydrogen (LH_2) tanks require adapted methods in preliminary aircraft design. Structural integrity must be ensured under both static and dynamic load conditions, including crash scenarios.
Classical preliminary design methods are limited in representing these new configurations. Finite Element Method (FEM)-based approaches provide a physics-based alternative that allows for early assessment of structural concepts. To address this need, the DLR Institute of Structures and Design (BT) has developed PANDORA (Parametric Numerical Design and Optimization Routines for Aircraft), a Python-based tool primary for parametric modeling, FEM analysis, and mass estimation.
Initially focused on global fuselage structure sizing, PANDORA has been extended to include detailed FEM models and dynamic analysis. Recent developments integrate geometry-based modeling with Open Cascade and CPACS, enabling flexible meshing and interdisciplinary exchange.

This paper presents these developments in two parts: first, the transition to geometry-based model generation; second, the application to double-shell LH_2 tank integration in the fuselage structure, analyzed under static load conditions.

1.1. Inputs and Definitions

In this paper the CPACS input is exemplary used from Faster-H2 DLR project where the tank shape geometry has already been tested for modeling of detailed tank models. The coordiante system used is shown in Figure 1 where the origin is the nose of the fuselage and x-axis is pointing towards the rear and y-axis to the right side of the aircraft.

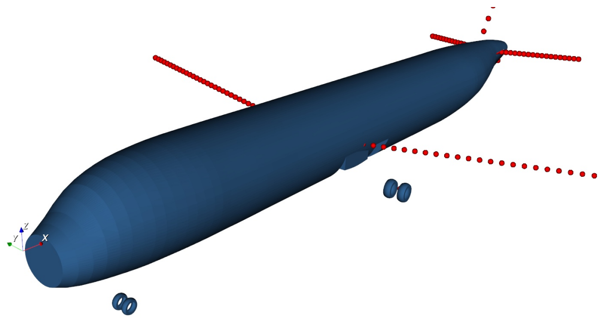

FIG 1. coordinate system used in this paper (and for most CPACS configuration)

2. PANDORA FRAMEWORK

The development of the PANDORA framework [1] started in 2016 for structural analyzes in aircraft pre-design using automated global FEM (GFEM) models in Multidisciplinary Design Optimization (MDO) workflows. The development goal was to create a framework to combine all developments of previous tools like TRAFUMO or SBOT+ [5] used for modeling global Finite Element Models (GFEM) of fuselage structure and sizing the structure to estimate the structural mass in multi disciplinary design (MDO) workflows. PANDORA is developed using Python 3 and open-source packages like:

- numpy and pandas for large array and table operations
- PyQt5 to build a GUI (graphical user interface)
- vtk for 3D visualizations
- OCC for geometry modeling
- GMSH for meshing of geometry

Available internal on GitLab https://gitlab.dlr.de/pandora and includes around 270 thousand lines of code. A rough overview about the main modules used in the PANDORA framework are shown in Figure 2.
The workflow described in this paper to analyze tank integration concepts uses multiple of the modules starting with reading of the CPACS (.xml) input file using Cpacs_Data module which is lxml based with some added features like managing unique identifiers (uID's) in CPACS by checking uniqueness or creating uID links. All aircraft parameters stored in CPACS for example:

- shapes of the fuselage or wings (defined by sections),
- materials, beam profiles or shell thicknesses,
- masses and loadcases,
- structural fuselage definitions like frames, stringers, crossbeams,
- landing gear positions.

Automated filling of the CPACS files with missing data for parameter studies or first estimations of the fuselage mass is done by the module CPACS_Design, creating a basic

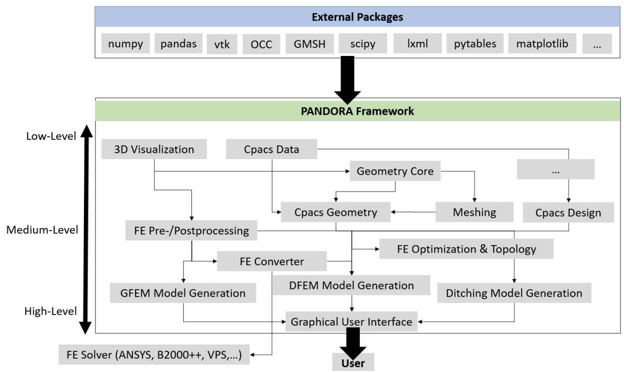

FIG 2. Rough overview of PANDORA framework main modules

fuselage structural layout including frames, stringers, or the center fuselage area for the wing coupling and landing gear bay cutouts with pressure bulkheads or tailplane attachment areas.
The fully filled CPACS file is used as input for the different model generators. The GFEM model generator reads the global structural parameters and directly creates the FE mesh with it's properties based on specific algorithms for each parameter. Only the surface of the aircraft is used as input to create frames and stringers like a regular mesh and other structural parts like bulkheads or crossbeams are created dependent on this regular mesh and by using uID links (for example a crossbeam is linked to a frame by its uID).
The FE models is build using the Pre-/Postprocesssor in PANDORA called FE_PYPREP to manage, access, modify and visualize all FE data. For example the FE model is checked for missing data or required inputs, nodes or elements can be selected by connectivity or meshes can be split or refined.
FE models in FE_PYPREP can be exported (or imported) using any implemented FE solver format in the FE_CONVERTER module for example interfaces to FE solvers like ANSYS, B2000++ or VPS are defined. Because most of the different solver formats use their own very specific ASCII based input format, the implementation level of importing/exporting is limited to the main required keywords but is open to extend. PANDORA itself stores the FE model data in a hierarchical structure, roughly visualized in Figure 3. This FE data is stored and managed using pandas DataFrames and can be directly exported to HDF5 files using the PANDORA internal structure. An interface to exchange the VMAP format (https://vmap-standard.org/) is planned to be implemented for standardized HDF5 exchange.

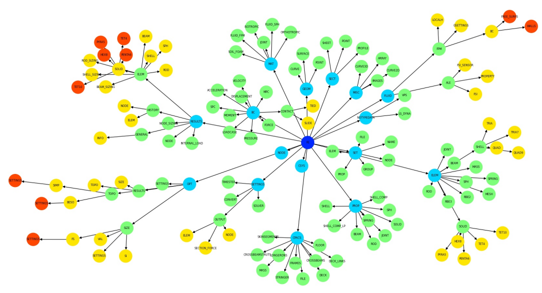

FIG 3. overview plot of all FE data categories in PANDORA

2.1. Geometry-based model generation

The previous (chapter 2) described GFEM model approach uses simplified parametrization in CPACS of specific structural components for example a structural frame-stringer-layout forming a regular grid is described by the x-position of the frame and the stringers by angles at different x-positions intersecting the fuselage skin. This parametrization is based on a common structural layout where the components are dependent from each other to build the GFEM model. For example if stringers are missing the regular GFEM grid cannot be build.
To analyze novel LH_2 concepts or other less common configurations, greater flexibility in parameterization and modeling is required. Accordingly, the PANDORA framework has been extended to incorporate a more general and detailed representation of models. This parameterization employs a comprehensive description of geometry and structural meshes using Open Cascade (OCC) in combination with mesh generators such as GMSH. The advantage of this approach is the independency from predefined parameters and structural components, so arbitrary structures can be modeled, but even so more parameters are required.
Both parametrization options have their advantages. The simple parametrization is faster and simpler to modify by the user e.g. for parametrization. The detailed parametrization is more complex to build and requires more performance, but is not limited by definitions or the level of detail.
A combination of both parametrization concepts have been implemented in PANDORA. For example, the fuselage structure is created by simple and fast parameterization at the GFEM level and the LH_2 tank is defined as DFEM model with detailed parameterization and both models are coupled afterwards (Figure 4). Also an automated conversion from simplified parameter description in CPACS into detailed parameter description is implemented using CPACS_DESIGN to variate parameters on global level and transfer them to detailed description.

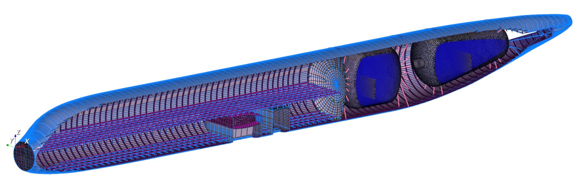

FIG 4. Example DFEM model (fuselage structure with LH_2 tanks)

2.1.1. interfaces for geometry and meshing

Three different Application Programming Interfaces (API) have been implemented in PANDORA to achieve detailed automated modeling.

- OCC-API (geometry interface between OCC and PANDORA)
- GMSH-API (mesher interface between GMSH and PANDORA)
- CPACS-GEOMETRY-API (parameter interface between CPACS and OCC-API, GMSH-API and FE_PYPREP)

First a Python OCC-API has been implemented to simplify the process of geometry creation, modification and usage. Because OCC is a low-level geometric modeling library that

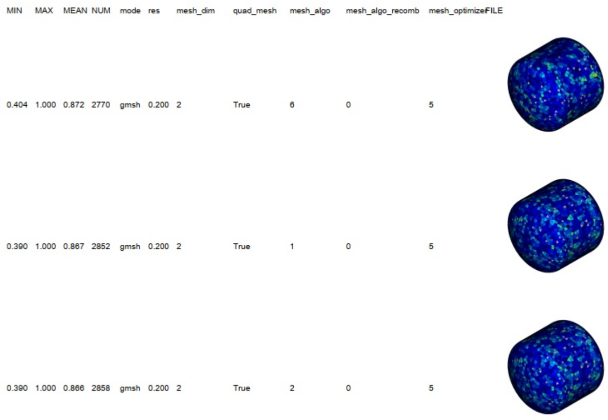

FIG 5. meshing tests with tank shapes using different GMSH algorithms

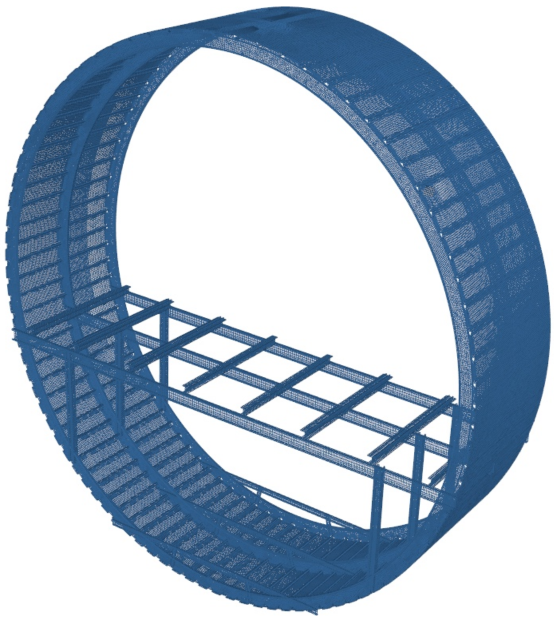

FIG 6. example of geometry based barrel with mouseholes at frame

requires an additional API to enable straightforward use in automated processes. Therefore each geometry object is handled with the same Python class and specific operations and conversions are done automatically or have been simplified in handling via Python.

Second to mesh the geometry an interface to GMSH has been implemented to directly convert the mesh into PANDORA FE format and set different meshign algorithms. As shown in Figure 5 some automated meshing tests have already been done, but there is still some work to do to achieve good-quality meshes.

And third, to parameterize the model generation, the xml-format has been used to build up an interface which can be directly integrated into CPACS and uses already defined data like shapes, materials or profiles. The CPACS-GEOMETRY-API uses basic geometrical descriptions like points, polygon-curves, bspline-curves, cuts, intersections, extrusions, fillings, coordinate transformations and more which using uID's to reference each other. The structural FE parts are described by basic meshing options like a geometrical reference, meshsize but also meshing algorithms, materials and properties.

2.1.2. example fuselage barrel section

As a demonstration, a fuselage barrel segment with integrated frames, stringers and cut-outs was created (Figure 6). The geometry is derived from CPACS input and automatically generated. Such fuselage sections enables systematic variation of structural layouts, e.g. different frame spacing, skin thickness, or cut-out dimensions.

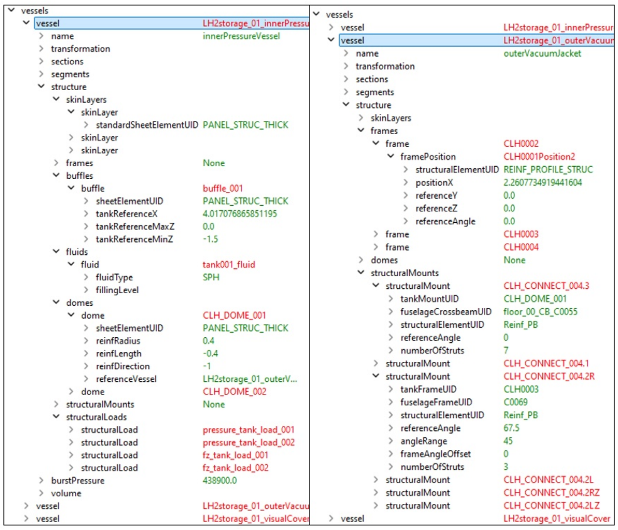

FIG 7. Example of simplified LH_2 tank parametrization in CPACS

3. LH_2 INTEGRATION STUDIES

3.1. automated model generation

In order to evaluate different integration strategies for cryogenic hydrogen storage, PANDORA was extended to automatically generate double-shell cylindrical LH_2 tanks. The parametric description in CPACS includes the outer and inner shell, domes, frames, baffles, different connection types, loads and fluid definitions as shown in Figure 7.

The conversion from simplified description in CPACS to detailed description is done automatically by PANDORA module CPACS-Design to describe the detailed model geometry and structure (Figure 8).

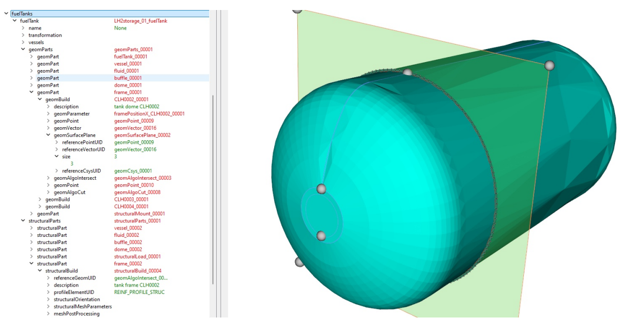

FIG 8. Example of detailed LH_2 tank parametrization in CPACS

3.2. concepts analyzed

To demonstrate the automated process in PANDORA, the following parameter studies have been done:

- variation of the number of tanks (1 large or 2 small tanks) with same total fluid volume
- variation of the gravimetric index (GI) to estimate tank loading
- variation of tank-fuselage-coupling concepts

3.2.1. variation number of tanks

The first variation by the number of tanks, 3 different basic options exist:

- A GFEM model of the fuselage structure without tanks but with loadings from the single tank (1T_M0) or two tanks applied to the structure using RBE3 elements (Figure 9)
- A GFEM model of the fuselage structure with DFEM model of the single tank (Figure 10)
- A GFEM model of the fuselage structure with DFEM models of the two tanks (Figure 11)

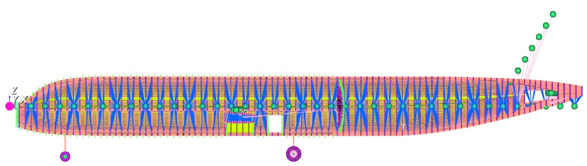

FIG 9. GFEM fuselage model with loading from single or double tank

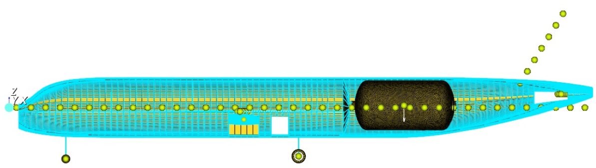

FIG 10. GFEM fuselage model with one tank

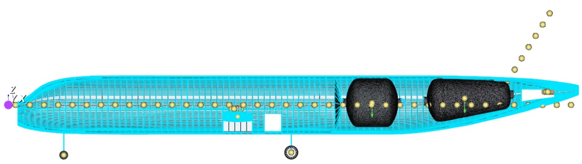

FIG 11. GFEM fuselage model with two tanks

3.2.2. variation gravimetric index

The second variation includes the gravimetric index (GI) which describes the ratio of the LH_2 fuel mass to the mass of the tank structure including fuel system components. Typically this ratio is between 0.2 and 0.35 for currently used concepts but can be expected to increase up to 0.5. The tank loads are calculated by the GI (which has been variated between 0.3, 0.4 and 0.5) and the fuel volume using a LH_2 density of 70.8 kg/m³ at 1bar of pressure. By using the total mass of each tank and its structural center of gravity the load for two simple flight loadcases have been added:

- +2.5G cruise flight maneuver loadcase
- -1.0G cruise flight maneuver loadcase

For both cruise flight loadcases the cabin pressure is calculated by a flight height of 12500m and a reference cabin pressure height of 2400m resulting in 0.578 bar. For the tanks 1bar of pressure is applied and additional the pressure from the reduced atmosphere pressure at 12500m resulting in 1.835 bar. To estimate the maneuver loading on the fuselage structure the total aircraft mass (exclude the tanks) is given by CPACS input as estimation of around 60 tons. The lift forces of the main wing are calculated by the gravitational load factor and applied to the wing DAM points expecting an elliptical load distribution. For the fuselage the load is estimated in the opposite direction of the wing forces and distributed constant (except the tank loads). Afterwards each loadcase is trimmed by iterative adjustment of the loads at elevator to avoid unbalanced loads and reactions forces in the FE model at the fuselage nose clamping (Figure 12).

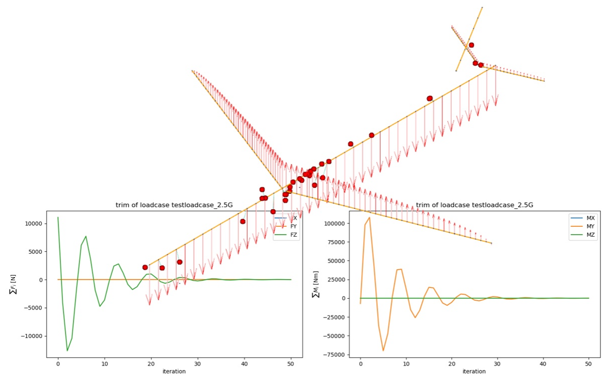

FIG 12. plot of masses from CPACS and simplified test loadcase with trimming results

3.2.3. variation of tank-fuselage coupling concepts

The third variation is the coupling concept between the tanks and the fuselage. Some concepts from previous research work already exist, such as dome spokes [6]. These have been used as reference to create simplified automated concepts for parameter variations. To structurally decouple the tank from the flight loads, only rod-elements (transfer only axial forces) have been used for coupling in the FE models. For all concepts, 3 struts in longitudinal axis of aircraft at the tank center frame for each side transfer acceleration forces in x-direction.

To transfer the gravitational forces from the tanks to the fuselage structure in y- and also z-direction, the three different coupling concepts at the tank endings are applied:

- coupling of tanks using dome spokes (Figure 13)
- coupling of tanks using frame spokes (Figure 14)
- coupling of tanks using crossbeams connection (Figure 15)

These couplings also carrying loads from rotations of the tank around the y- and z-axis.

Rotational degrees of freedom of the tank around y- and z-axis are constrained by these connections and the x-axis is constrained by spokes from the center tank frame in z-direction and coupled with the fuselage frame. First simulations have shown that bending of the fuselage structure in flight loadcases effects that these z-spokes transfer flight-loads from the fuselage to the tanks (Figure 34).

To reduce the tank loading from flightloads additional modified concepts have been added with dome and frame spokes using angular offsets instead of z-spokes (like bi-

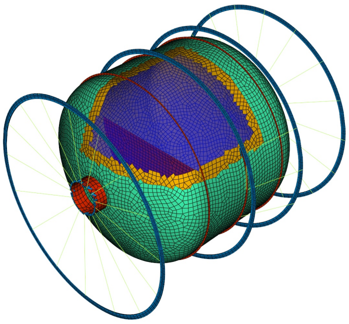

FIG 13. Tank coupling concept of dome spokes

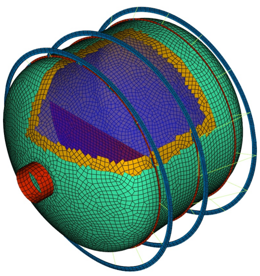

FIG 14. Tank coupling concept of frame spokes

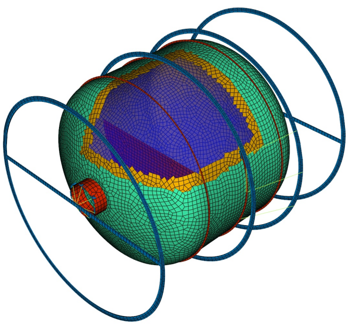

FIG 15. Tank coupling concept of crossbeam connection

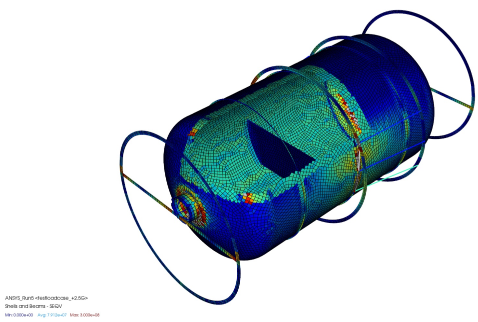

FIG 16. Example of z-strut causes stresses at tank center structure under flightloadcase +2.5G

cycle spokes) as seen in Figure **??** and **??**. Using angular offset the rotation of the tank around x-axis causes axial forces in the spokes to constraint the rotation without using z-spokes at the center tank.
For the crossbeam connection concept an additional concept with spokes in z-direction at the endings has been

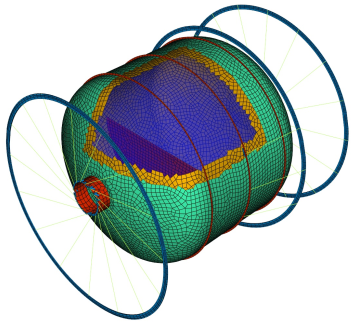

FIG 17. Tank coupling concept of dome spokes with angular offset to avoid rotational movement

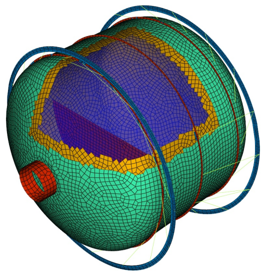

FIG 18. Tank coupling concept of dome spokes with angular offset to avoid rotational movement

added to reduce the load on the crossbeam and on the central tank z-spokes (Figure **??**).

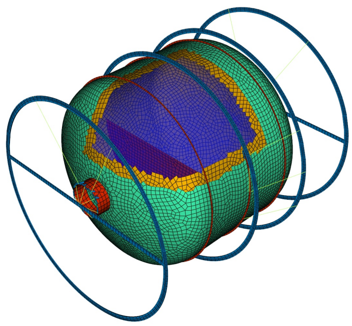

FIG 19. Tank coupling concept of dome spokes with angular offset to avoid rotational movement

3.2.4. detailed model generation

The process to build the FE models starts with the basic CPACS input file which is modified by automated scripts to return a specific CPACS file for each parameter set by scaling the tank, moving frame positions or defining tank mounts.
Cpacs_Design module of PANDORA uses the specific CPACS input into build a detailed geometry and structure definition in CPACS like a step-by-step recipe for the DFEM model generator. The simplified flight loadcases are estimated using Cpacs_Design as described in 3.2.2 and the specific tank positions, fluid volumes, gravimetric indices and load factors are used to calculate the additional tank loads for each flight loadcase and trimming the loadcase.

The CPACS input with all detailed parameters for the DFEM tank model generator and the basic parameters for the GFEM fuselage model generator is used to build the fuselage GFEM model in PANDORA. Afterwards each single part of the DFEM tanks is generated using OCC geometry and meshed by the mesher (in this paper GMSH is used but different mesher should be integrated in the future). Based on the hierarchical CPACS format and the object oriented design of the CPACS_Geometry_API each component is handled independent form each other but connectivity and relations are linked. For example if the user only wants to model the tank frame only linked and required objects are generated and cached in OCC based GeometryCoreAPI.

If the user requests to model the whole tank structure, all required sub components are automatically generated, meshed, materials and properties set and optional post-mesh operations are executed like conversions from beams to shells be extrusions or conversion from solid meshes to SPH elements for dynamic fluid simulations. As result all component FE models are autoamtically merged to a single FE model but keeping their references to the CPACS object by using the same uID as set name.
Because all DFEM components are modeled independent from each other, the connectivity of all components to each other is described in CPACS as structuralMount where different components an their conenctivity can be defined for example by defining a search radius, a maximum number of connection and a connection type like RBE2, RBE3 or BEAM-elements with section properties (Figure 20). If components sharing the same mesh edges nodes are merged directly and mesh connectivity can also by checked with PANDORA (Figure 21).

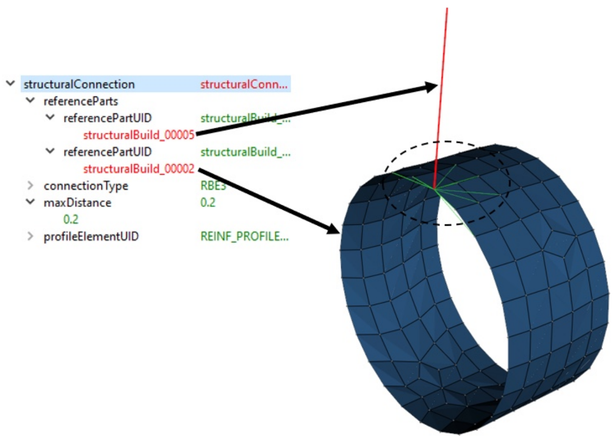

FIG 20. Example of definition of connectivity in detailed CPACS and FE modeling

3.2.5. model sizing

After the model generations is completed the sizing starts automatically using linear implicit analyses with ANSYS as FE solver. Fist the model is prepared by selecting the sizing region and optional split the property cards by element sets and connectivity into multiple regions which are sized independent. For example the initial property cards after model generation from CPACS are shown in Figure 22. In this paper the free sizing is used to split all shells into independent

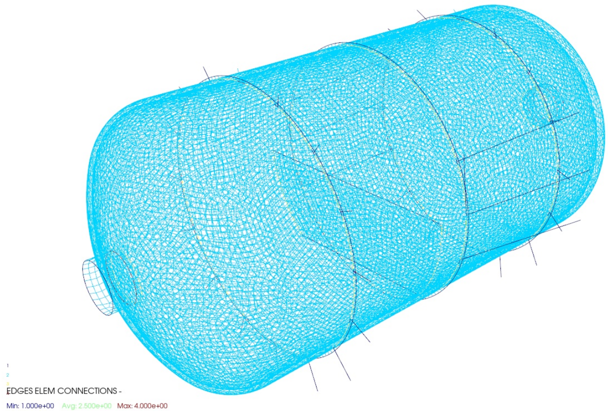

FIG 21. Example of checking tank mesh connectivity in PANDORA

property cards, Figure 23, to compare the results without grouping.

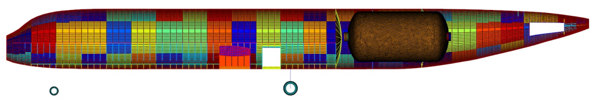

FIG 22. Property cards as defined in CPACS

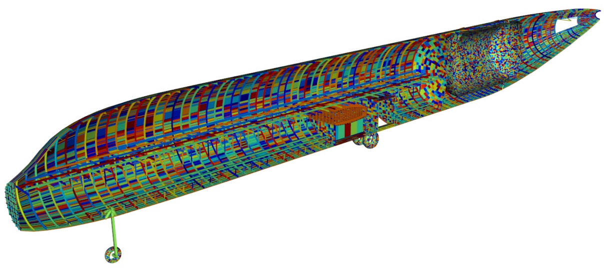

FIG 23. Property cards after free sizing initialization

After initializing the FE model for sizing the iterative process is started using the FE_Converter of PANDORA to export the FE model for any implemented solver format, run the simulation and import the results again into PANDORA. In this case ANSYS as linear static FE solver is used.
The latest results of each iteration for all loadcases are used to adjust the shell and beam elements properties based on different criteria. For Beam elements a strength criteria is implemented to scale the profile sheet thickness or profile shape itself based on the maximum allowed material stress and required safety factor defined in CPACS (or in the FE model material data). For Shell elements the strength criteria is defined as well and a Bruhn buckling criteria based on shell geometry and material stiffness and local element stresses the safety factor against buckling is calculated and used for sizing the shell thickness.
A new fatigue criteria using loadcycles from different loadcases and multiplications is also implemented based on rainflow algorithms to calculate the number of cycles and cycle-amplitudes for fatigue lifetime estimation using material Wöhler curves. Because this criteria is still in development and not validated, it has not been used to estimate the fuselage structure mass.
An exemplary convergence of shell and beam mass is shown in Figure 24. After 5 iterations only minor changes in

mass appear - so in the following studies the fuselage mass has been estimated by using only 5 iterations to reduce the simulation time.

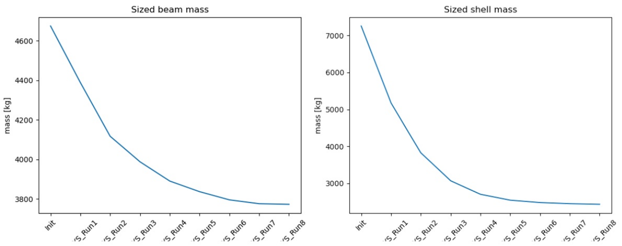

FIG 24. Example convergence of sizing iterations for shell and beam mass of fuselage structure

3.3. comparison of concepts

The following tank coupling concepts (as described in chapter 3.2.3) have been analyzed and compared to each other using the below given abbreviations in brackets:

- only GFEM with tank loading (M0) - Fig. 9
- dome spokes and z-spokes at center (M1) - Fig. 13
- frame spokes and z-spokes at center (M2) - Fig. 14
- crossbeams and z-spokes at center (M3) - Fig. 15
- dome spokes with angular offset (M4) - Fig. 17
- frame spokes with angular offset (M5) - Fig. 18
- crossbeams and z-spokes at endings and center (M6) - Fig. 19

And for the number of tanks the abbreviation is used:

- large single tank (1T)
- two small tanks (2T)

The estimation of the sized fuselage mass (Figure 25) compares all concepts (based on 42 different studies) for a variation of the gravimetric index (parameter of tank loading, lower GI means higher loads for same LH_2 volume). As expected the M0 concept (GFEM model with simplified tank loads) underestimates the fuselage mass in this simplified case by around 6%. When using more suitable loadcases like in MDO loops and using more sizing criteria like fatigue, the mass difference could be expected to increase even more because of local load peaks caused by the tank connections.

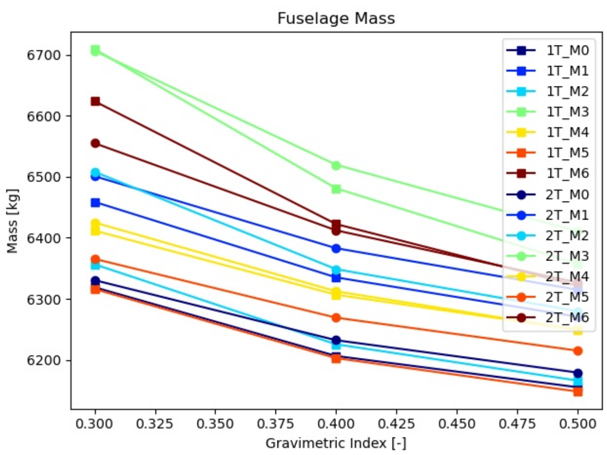

FIG 25. sized fuselage structural mass for different tank integration concepts

Additionally the same concepts have been calculated with fuselage and tank structure sized. These tank masses are not plausible due to missing of relevant tank load cases but they can be used to compare these concepts by their potential. Figure 26 shows the total tank structure masses (domes, inner and outer vessels, spokes and crossbeams) for concepts with one tank and for two tanks in Figure 27.

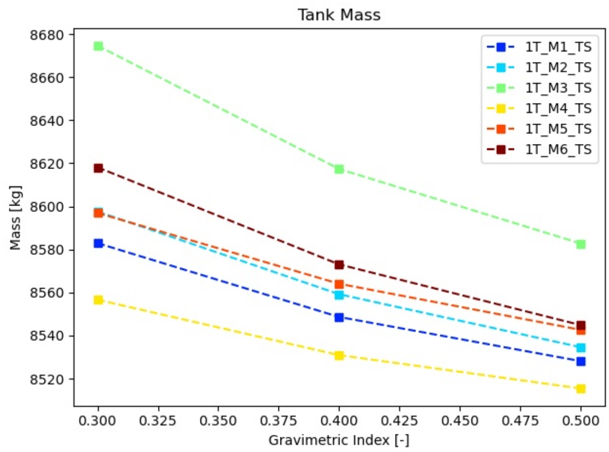

FIG 26. sized tank structural mass for single tank integration concepts

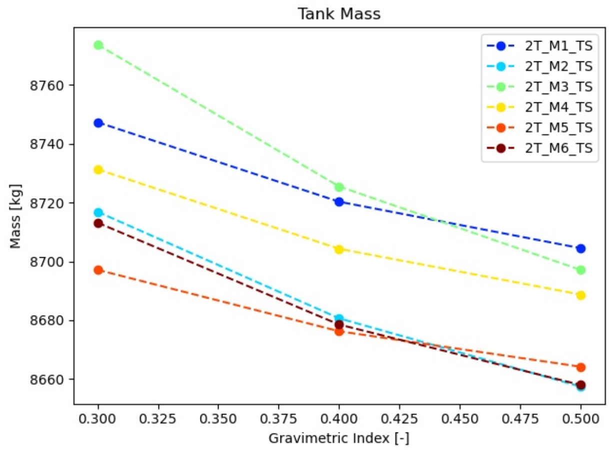

FIG 27. sized tank structural mass for two tank integration concepts

Looking at the thickness results after 5 iterations of sizing the gfem fuselage (Figure 28) shows less increased thickness in the tank area due to smeard loading using RBE3 elements to apply loads. Compared to the 1T_M3 concept with highest fuselage mass (Figure 28) shows local areas of increased thickness where the DFEM tank is attached.

3.4. stress comparison of fuselage

The concept with the highest fuselage stress level (resulting in heighest strucutral mass) is shown in Figure 30 before starting sizing process and after 5 iterations of sizing (Figure 31). In the inital stress plot the center fuselage bulkheads are stressed and the rest of the fuselage is less loaded. After sizing the stresses are more equalized and peaks reduced.

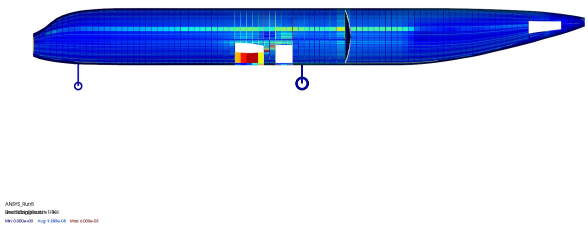

FIG 28. fuselage thickness results (5 iterations) for GFEM model with loading of one single tank (1T_M0)

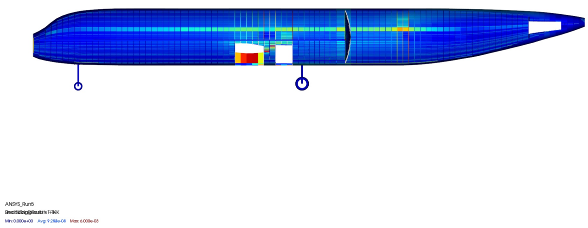

FIG 29. fuselage thickness results (5 iterations) for GFEM model with single DFEM tank (1T_M3)

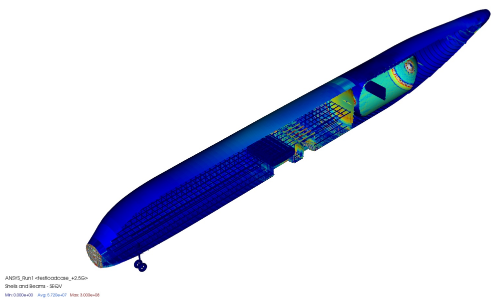

FIG 30. fuselage stress before sizing for concept with single tank and crossbeam connection (1T_M3)

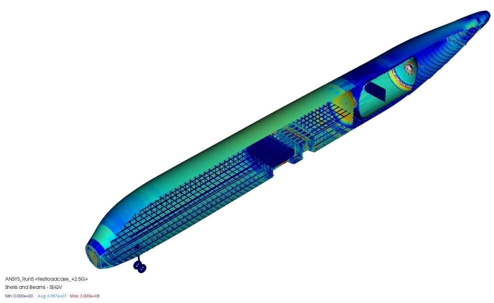

FIG 31. fuselage stress after 5 iterations for concept with single tank and crossbeam connection (1T_M3)

3.5. stress comparison of tanks

Comparing all stress plots shows that the concept M3 with crossbeam tank connection causes the highest stress levels in the tank structure (Figure 32).

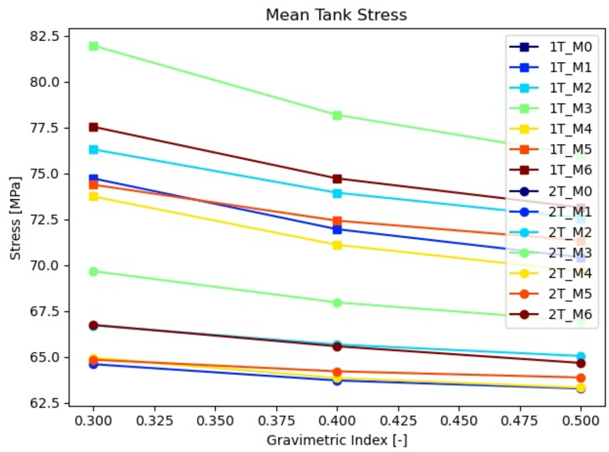

FIG 32. comparison of mean tank v. Mises stresses for all concepts and different GI

The detailed stress plot shows the loading of the central tank structure around the z-spokes because less load is transferred to the crossbeams. For the smaller tank of the 2T_M3 concept the stresses are more transferred to the tank frame (Figure 33) than for the large single tank concept 1T_M3 (Figure 34). But compared to the other concepts the tank is more stressed. But this concept should also be considered in upcoming concept studies but with stiffer crossbeam structures.

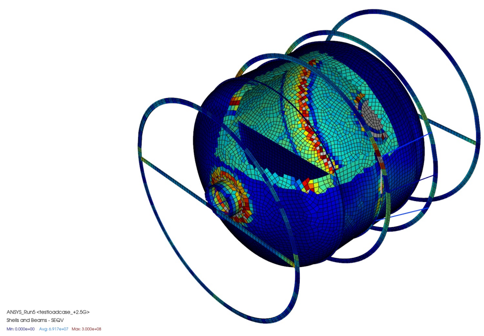

FIG 33. first tank of 2T_M3 concept showing v.Mises stresses during +2.5G loadcase

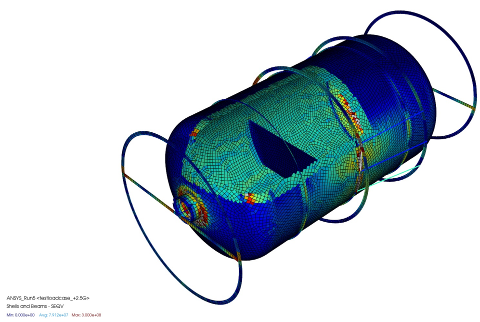

FIG 34. single tank of 1T_M3 concept showing v.Mises stresses during +2.5G loadcase

The lowest tank structure stress level is shown by the M1 and M4 concepts. The double tank concept shows less stresses during the +2.5G flight loadcase (Figure 35). The larger single tank concept shows best tank stress results with concept M4 (dome spokes with angular offset) - Figure 36. For larger tank lengths an integration concept without central z-spokes should be used to decouple from fuselage bending.

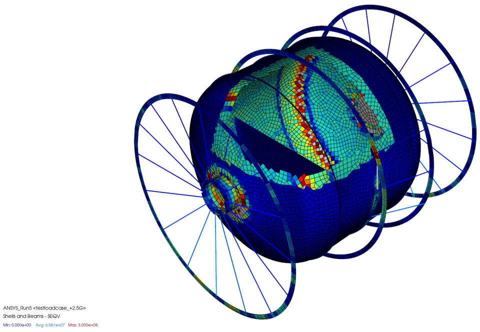

FIG 35. first tank of 2T_M1 concept showing v.Mises stresses during +2.5G loadcase

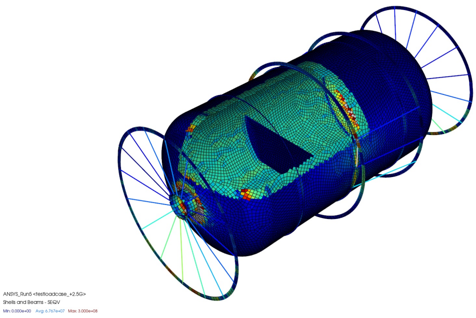

FIG 36. single tank of 1T_M4 concept showing v.Mises stresses during +2.5G loadcase

3.6. summary of first results and limitations

First analyses confirm the feasibility of using PANDORA for automated geometry generation and FEM analysis of integrated LH_2 tanks. The parametric approach enables efficient variation of different parameters like tank size, position and structural connections. The results highlight the trade-off between structural efficiency and integration complexity, underlining the importance of automated tools for systematic evaluation in the early design phases.
Going towards automated and detailed full aircraft FEM models also shows that the computational performance is limited and more efficient algorithms using multi-thread and better memory handling are required.

4. OUTLOOK

4.1. crash and ditching simulations

A next development step is the extension of the automated DFEM models towards transient crash and ditching simulations. For this purpose, tank and fuselage structures will be modeled with higher resolution in critical areas, combined with fluid-structure interaction (FSI) capabilities for sloshing effects [4]. This enables the assessment of the safety requirements for unconventional energy storage systems in emergency scenarios.

4.2. detailed static simulations

In addition to crash analyses, detailed static simulations will be carried out for different integration concepts. This includes nonlinear material modeling, local buckling effects, and more accurate representation of load introduction and connections.

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