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ADVANCING SUSTAINABLE MARINE PROPULSION: COMPOSITE FUEL STORAGE TANKS FOR NEXT-GENERATION NH3-POWERED SHIPS

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Abstract

Maritime transport routes are vital for Europe as a key player in the global economy. The European Commission is seeking to transform it into a smart, green system, with the European Green Deal strategy targeting a 90% reduction in emissions by 2050 through sustainable alternatives. Ammonia (NH3) as an energy carrier offers the potential for fossil-free ship propulsion systems. However, storage of NH3 for use in the propulsion system is subject to specific operational and design space requirements. Specifically, storage solution must maximize NH3 capacity within limited installation space while ensuring compatibility with existing containerized arrangements for seamless integration into existing vessels, because NH3 requires three times the storage space for same energy output as compared to conventional fuels. Composite fibre-reinforced polymers, with their outstanding mechanical properties, combined with excellent chemical resistance and low density, offer the possibility of designing NH3 lightweight pressure vessels that make optimal use of the available installation space. The methodology involves design space exploration, optimization, and verification through structural analysis of fibre reinforced composite tanks to ensure safety and structural integrity for maximizing storage efficiency. This study promotes sustainable maritime transportation, paving the way for environmentally conscious and commercially viable NH3-fuelled marine propulsion systems.

1. Introduction

Transport is vital for the European Union's cohesion and global trade growth, yet its carbon footprint has escalated, now constituting a quarter of the EU's greenhouse gas emissions, a trend that continues upward. The European Commission is actively addressing this, notably through the European Green Deal Strategy, which aims for a 90% emissions reduction by 2050 [1]. Waterborne transport, responsible for the largest share of cargo movement, is responsible for 13% of all greenhouse gas emissions [2]. To combat this, innovative solutions like NH3 as a fuel in maritime domain are being explored. However, specifically the fuel NH3 despite being carbon-free, poses specific challenges in its utilization. Storage presents a significant issue, as it necessitates nearly three times the space of heavy fuel oil in its liquid form for equivalent energy output [3]. Therefore, this research aims to demonstrate innovative NH3 storage with the help efficient storage tanks. Metallic storage tanks have been standard [4,5] in maritime applications due to their durability and reliability for storing fuels like LPG, diesel and heavy oils. On the other hand, composite storage tanks offer lighter weight, corrosion resistance, enhancing efficiency and structural integrity. Depending on vessel type and size, the composite tanks may be tailored for different design spaces enabling higher and more efficient capacity storage as compared to traditional metallic tanks. In order to compare and explore the most efficient storage solutions, it is necessary to examine the classifications and characteristics of various tank types used in gas storage.

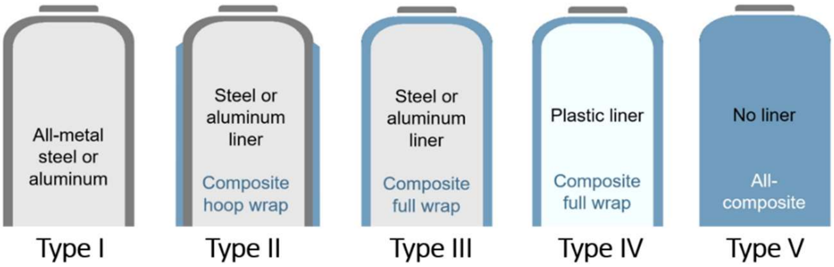

Figure 1. Types of storage tanks as in [6].

As shown in Fig. 1, storage tanks can be classified in five main types, viz., I, II, III, IV and V [6]. Type I tanks represent the predominant use of all-metal tanks, designed specifically for high-pressure tasks such as compressed natural gas storage. Type II tanks, characterized by metallic liners and composite hoop wraps, provide lighter alternatives with high-pressure capabilities, commonly utilized in Compressed Natural Gas (CNG) and hydrogen storage. Type III tanks strike a balance between weight and durability by employing fully wrapped metal liners, making them suitable for medium-pressure applications like compressed hydrogen storage. Type IV tanks, made entirely from non-metallic materials while being reinforced with full composite wrap, provide lightweight, corrosion-resistant solutions suitable for low to medium-pressure applications like CNG and hydrogen storage. Finally, type V tanks leverage advanced composite materials and construction methods, excelling in lightweight, high-pressure environments, particularly in hydrogen storage for fuel cell vehicles. As this study targets efficient storage of NH3 in the low-medium pressure range, type IV tanks are considered superior to type I, II and III due to higher gravimetric efficiency [7]. Establishing corrosion resistance through plastic liner and strength through full composite wrap, the filament-wound type IV composite tanks offer a lasting solution for storing gases in demanding environments. Therefore, this work describes systematic design and development of type IV composite fuel storage tanks to maximize storage efficiency through analysis of operational conditions, available design space and verification through structural calculations to realize safe and efficient NH3 storage and transportation in maritime shipping.

2. Methodology

This research follows a structured three-step methodology as illustrated in Fig. 2 to ensure the development of efficient NH3 storage tank for maritime storage and propulsion. Initially, material selection is meticulously undertaken, considering aspects such as operational temperature and pressure, nominal strength requirements, and compatibility with marine conditions. Subsequently, the geometry is determined, in terms of cross-section and dimensions of the tank assembly. The tank is designed to maximize storage efficiency, quantified by the metric "gravimetric efficiency," and to fit within the available design space, based on preliminary finite element analysis. Lastly, a feasibility assessment of the aforementioned tank is conducted through rigorous structural analysis with all applicable load cases as stated in international maritime rules and regulations. This critical step ensures that the chosen design can withstand the dynamic stresses and pressures encountered during storage and transportation, thus confirming its practical suitability for maritime applications.

By systematically addressing material selection, optimal geometry determination, and feasibility analysis, this methodology ensures development of robust and efficient NH3 storage systems tailored for the maritime industry.

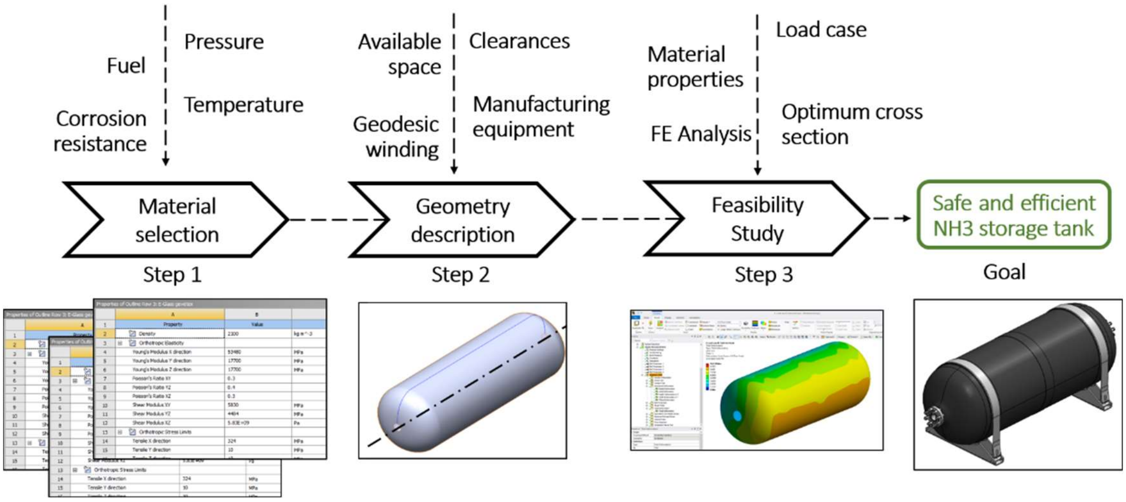

Figure 2. Stepwise methodology for constructing safe and efficient storage tanks

3. Outcomes

This section outlines the results obtained from following the aforementioned stepwise methodology.

3.1. Step 1: Material selection

For storing NH3 in marine environments, it has been identified that the operational temperature is in the range of -33°- 45°, while the design and burst pressure are 1.0 MPa and 2.0 MPa respectively. NH3 has alkaline properties and is corrosive. Considering these requirements, three materials have to be selected for type IV tanks, viz., fibre reinforcement, resin system and plastic liner.

E-CR (E-Glass Corrosion Resistant) glass fibers [7] have been regarded as the optimal choice for storing NH3 by considering an exemplary nominal fibre strength of 2760 MPa mentioned in [8], low thermal expansion coefficient [9] and corrosion resistance. A compatible resin system consisting resin Araldite LY 556, hardener Aradur 917-1 and accelerator DY 070 [10] that is used widely in aerospace domain, is regarded as an adequate option for fabricating the laminate.

As the liner of type IV composite tanks is considered as non-load bearing, material selection is carried out only based on chemical reactivity and permeability of liner material against NH3. Since the material Polyamide 6 (PA6) has good chemical resistance [11] , very low estimated permeability towards NH3 [12] and is commonly used as a liner for type 4 tanks [13], it emerges as the preferred choice as the primary barrier for NH3 storage.

Considering E-CR glass fibre and resin system Araldite LY 556, hardener Aradur 917-1 and accelerator DY-070, the Glass Fiber Reinforced Plastic (GFRP) ply properties are obtained from material library of Altair ESAComp as listed in table 1 & 2 and are used for structural analysis of the tank.

Table 1. GFRP ply mechanical properties [14] from Altair ESAComp

	ρ (Kg/m^3)	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	G_{12} (GPa)	G_{23} (GPa)	G_{13} (GPa)	ν_{12}	ν_{23}	ν_{13}
GFRP Ply	2100	53.4	17.7	17.7	5.8	4.8	5.8	0.3	0.4	0.3

Table 2. GFRP ply failure properties as per safety factors described in [8]

	χ_1 (MPa)	χ_2 (MPa)	χ_3 (MPa)
GFRP Ply	324	10	10

where, ρ is density, E_i is Young's modulus in i-direction, G_{ij} is Shear modulus in ij-plane, v_{ij} is poissons ratio in ij-plane and χ_i is tensile strength in i direction. i=1 (fibre direction), 2 (in-plane transverse direction), 3 (out of plane direction).

3.2. Step 2: Geometry description

In step 2, the external geometry of the tank is determined in two sub-steps. First, based on available space in the target location, the design space is identified and a parametric analysis is carried out for finding optimal cross section. Subsequently, the geometry of the tank is determined based on isotensoid loading scenario on aforementioned optimal cross section, followed by filament winding simulations.

3.2.1 Determination of design space and optimal cross section

The TEU (Twenty-foot Equivalent Unit) standardizes containerized cargo, streamlining global shipping operations. Therefore, the composite tanks are designed taking into account parameters such as available space in the TEU, manufacturing limitations and clearance requirements during assembly while maximizing fuel storage. Fig. 3a illustrates a drawing of 8-tank assembly inside the TEU with necessary distance clearances.

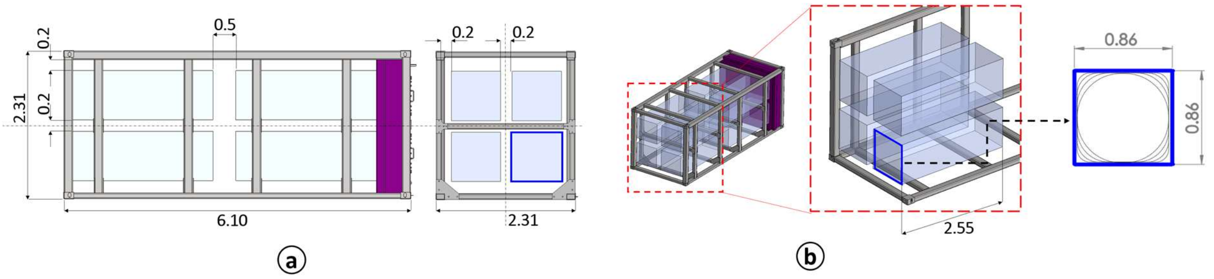

Figure 3. a) Clearance requirements and arrangement in TEU, b) Design space

As per clearance requirements identified from assembly of auxiliary systems and inspection for regular maintenance, a tank system is designed with minimum axial surface clearance of 0.5 m and lateral surface clearance of 0.2 m. Based on this requirement as illustrated in Fig. 3b, available design space is identified as a cuboid with side length 0.86 m and axial length 2.55 m for type IV composite tank. However, as highlighted inside blue box in Fig. 3b, the composite fuel storage tanks can be fabricated in various cross-sectional shapes. Therefore, a parametric study was conducted to determine the most optimal cross-section in terms of gravimetric efficiency, as shown in Fig. 4.

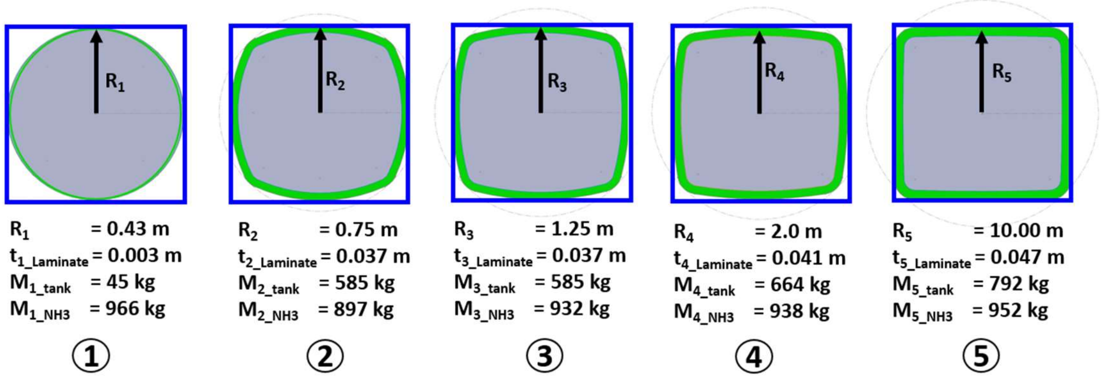

Figure 4. Parametric analysis of cross sections within design space

A simplistic Finite element (FE) analysis aimed to quantify the required laminate thickness for all cross-section variants has been carried out. The analysis is conducted on tanks with identical composite layup and with length of 2.55 m with the cross-sections as illustrated in Fig. 4. The tanks are fixed on one end and allowed to expand in axial direction under an internal pressure of 2 MPa. Tank with cross sections radius R_i requires a GFRP laminate thickness of $t_{i\_Laminate}$, stores M_{i_NH3} of NH3 mass and weighs M_{i_tank} where variant ID i=1, 2, 3, 4 & 5. It can be seen that although all tanks store similar amounts of NH3 by mass (ranging from 890-960 kg), the tanks with rectangular cross section require significantly more wall thickness. The aforementioned extra wall thickness is necessary to avoid failure due to compressive stresses formed at the edges of the rectangular cross section after deformation. For example, variant 1 with circular profile requires only 3 mm thickness whereas variant 4 with almost rectangular profile requires 41 mm thickness while storing similar amount of NH3. The disparities between weight of a particular tank variant and its corresponding storage capacity may be quantified and compared with the storage efficiency metric called "Gravimetric efficiency", which is defined as the ratio of mass of stored fuel and total mass of the system, and is given by equation:

$$\text{Gravimetric efficiency}_i = \frac{M_{i\_NH3}}{M_{i\_NH3} + M_{i\_tank}} \tag{1}$$

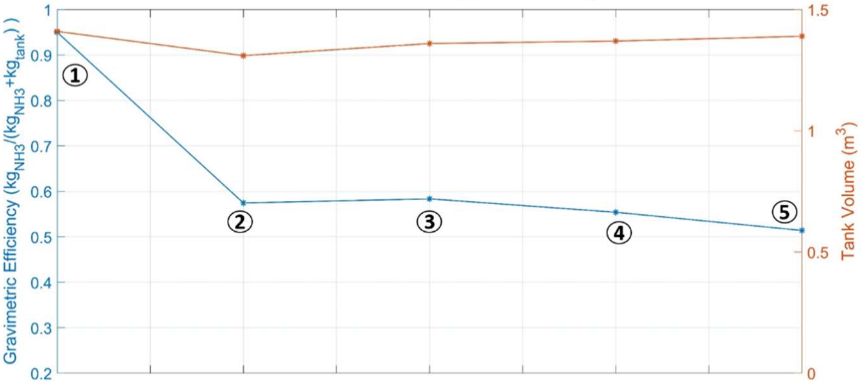

Figure 5. Gravimetric efficiency of parametric variants 1, 2, 3, 4 & 5

In Fig. 5, corresponding gravimetric efficiency values are plotted. It can be observed that the tanks with circular cross section have highest gravimetric efficiency when the mass of the overwrapped fiber reinforcements is considered. Therefore, although rectangular cross-section may appear more modular and space efficient, it is concluded that for composite tanks, the circular cross section variant is the most optimum for maximizing gravimetric efficiency in a cuboid design space. Therefore, based on this preliminary analysis, geometry with circular cross section is selected for further analysis and verification.

3.2.2 Isotensoid design and winding of external profile of liner

The selected circular geometry of a type IV composite at plastic liner is assumed "isotensoid" i.e. in uniform tension due to internal pressure. Relation between axial ($\bar{z}$) and radial location ($\bar{r}$) defines the shape of an isotensoid profile by the following equation [15]:

$$\bar{z} = \int_1^{\bar{r}} \frac{\bar{r}^3 d\bar{r}}{\sqrt{(1-\bar{r}^2)(\bar{r}^2-\bar{r}_1^2)(\bar{r}^2+\bar{r}_2^2)}} \tag{2}$$

$$\bar{r}_{1,2}^2 = \frac{1}{2}\left[\sqrt{\frac{1+3\bar{r}_0^2}{1-\bar{r}_0^2}} \mp 1\right] \tag{3}$$

Normalized pole opening radius ($\bar{r}_0$) is given by ratio of r_0 to R where r_0 and R are the pole opening radius and maximum radius in the cylindrical area of the tank. r_0 is defined to match the outside radius of metal insert with a standard DN100 flange, i.e., 64 mm. R is defined as 416 mm and is derived from the allowed maximum dimensions of the tank based on clearance constraints, manufacturing requirements and available space in the TEU. After numerically integrating over all radius values ranging from r_0 and R and solving the integral Eq. 2, a contour distribution as shown in Fig. 6a is obtained for axial locations which is then revolved around an axis in CAD program (SolidWorks) to obtain a 3D CAD file of the composite tank. Subsequently, filament winding simulations are carried out as shown in Fig. 6b for accurately defining laminate thickness as illustrated in Fig. 6c.

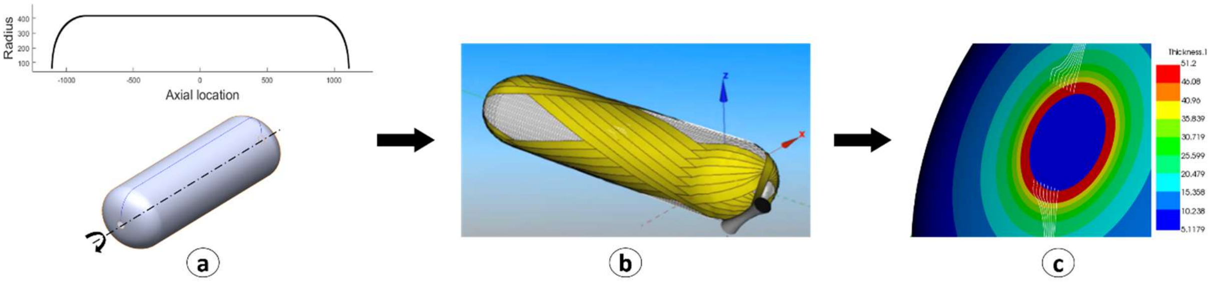

Figure 6. a) Contour and 3D model, b) Winding simulations, c) Thickness distribution

The layup of [$\pm 8.85_4 \quad \pm 89_4$], obtained from preliminary thickness estimation calculations [8] consists four dual-pass (positive & negative) plies with helical and hoop winding at 8.85° and 89° respectively. This layup results in 8 mm laminate thickness at the cylindrical part of the storage tank, whereas 52 mm thickness at the dome area as a result of filament winding simulations as illustrated in Fig. 6c.

3.3. Step 3: Feasibility study

In this step, the aforementioned data is compiled and imported to finite element program to verify the design with detailed structural analysis. The CAD file is imported in finite element program ANSYS along with thickness and winding angle definitions of the laminate from winding simulations as illustrated in Fig. 6, where the tank rests over two curved metallic supports, and is held in place in TEU frame with the help of tension-straps as in Fig. 7. Rubber cushioning is provided between metallic components and composite surface to prevent surface damage through direct surface contact.

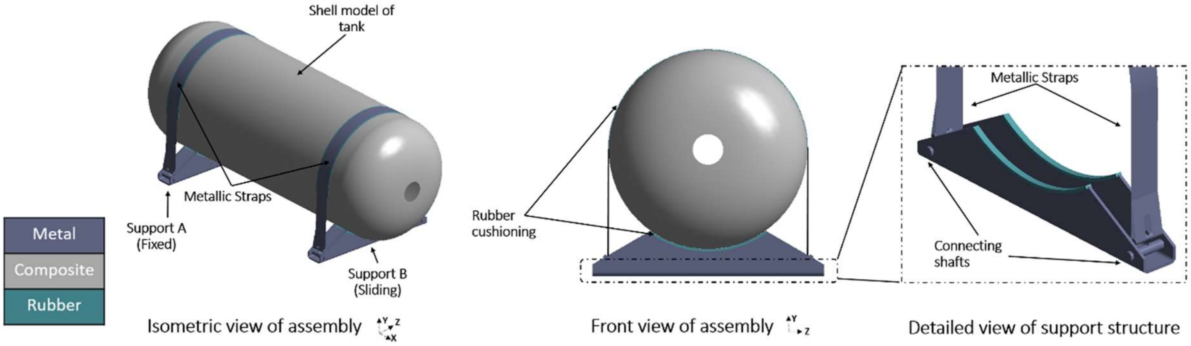

Figure 7. Assembly in ANSYS

As illustrated in Fig. 7, the entire assembly following the geometry import is discretized with 89685 elements that are a mixture of solid (TET10, HEX20) and shell elements (QUAD8) in ANSYS. Particularly, the tank and metallic straps are modeled with shell elements, whereas the rest of the assembly is modeled with solid elements. Liner bonded contacts have been defined between composite tank surface, rubber cushioning and metallic straps. Models with refined mesh and solid elements are created for boss region as in Fig. 8b and support-connection areas as in Fig. 8c of the tank with 9174 solid elements (HEX20) and 37597 solid elements (HEX8) respectively for examining stress concentration areas with higher accuracy. As per [16], load cases have been defined as a requirement for qualifying the design of tank in marine environment viz., static and dynamic loads in horizontal orientation, static and dynamic loads at 30° heeling, sloshing loads, buckling check, accidental scenarios of flooding as well as collision forward and backward, and lastly testing loads.

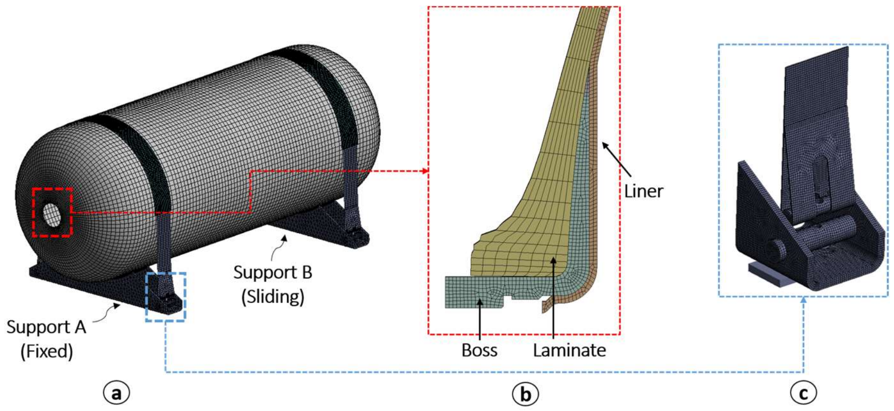

Figure 8. FE models: a) Global model, b) Detailed model of boss, c) Detailed sub-model of supports

After examining the results of all load cases for aforementioned assembly, it was concluded that load case titled "testing loads" is most structurally demanding and worst-case scenario due to significantly higher (test pressure, 3 MPa) internal pressure load as compared to other load cases (burst pressure, 2 MPa). Therefore, in Fig. 9, this article highlights the finite element analysis of aforementioned worst-case scenario. For evaluation and qualification of design, Cuntze failure mode 1 (tensile failure in fibre direction) is used as an acceptance criteria for the composite tanks [17] aligning with the assumption that filament wound composite tanks are primarily under tension [8].

For load case "testing loads", support A is fixed and support B is allowed to slide in axial direction to allow slight expansion due to pressurization. In addition to self-weight of the tank assembly, a conservative estimate of 1000 kg of fuel weight is considered. A hydrostatic pressure of 3 MPa is applied on the internal surface of the tank and results are evaluated using Cuntze acceptance criteria.

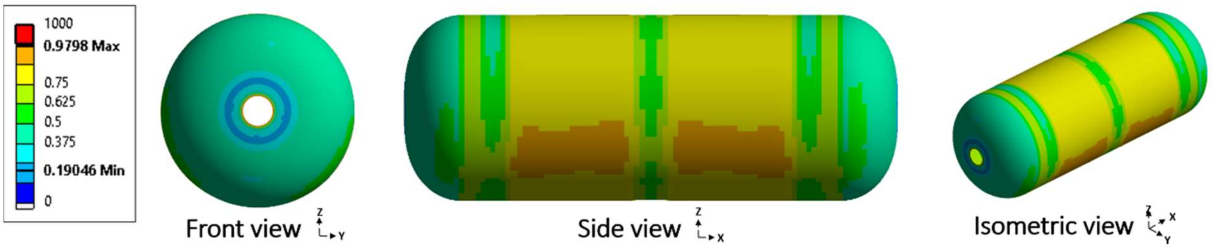

Figure 9. Cuntze failure mode 1 distribution for global model of tank

As seen from Fig. 9, the maximum value of Cuntze failure mode 1 reaches up to 0.9798 for the given laminate. Since the value does not surpass 1 at any point of the laminate, the circular cross-section design of the tank for the composite layup of $[\pm 8.85_4 \ \pm 89_4]$ is safe for the worst load case scenario. Similarly, for detailed models described in Figs. 8b & 8c, the maximum value of Cuntze failure mode 1 reaches 0.85, whereas the maximum von-Mises stress in steel supports reach 163 MPa, while allowable value being 340 MPa. Therefore, the assembly model is considered to be safe for worst load case, thereby qualifying the design of the tank assembly.

4. Discussion

This study successfully demonstrates the proposed methodology for designing composite fibre-reinforced tanks for storing NH3 in maritime propulsion systems. Systematically focusing on material selection, design exploration and optimization for gravimetric efficiency, and validation via structural analysis, this research addresses key challenges in NH3 storage, prioritizing space efficiency and compatibility with existing vessels.

To summarize, materials were successfully selected based on operational, compatibility and design space requirements for storage of NH3 in marine environments. Design space was determined and explored using parametric analysis, that resulted in optimum cross section for the composite tank. The geometry of the optimum cross section was determined using analytical equations, followed by winding analysis. Lastly, the determined geometry was verified through detailed structural analysis as per international rules and regulations.

In conclusion, this study represents a crucial step towards greener maritime transport. The composite tanks offer a practical and commercially viable option for NH3 storage, paving the way for a future where environmental responsibility and economic success coexist. Ongoing research will further refine these solutions, accelerating the adoption of sustainable marine propulsion systems.

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