# COMPARISON OF A COMBINED TORUS TANK WITH A COMPOSITE ISOGRID SUPPORT WITH EXISTING DESIGN SOLUTIONS

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## INTRODUCTION

A review of the structures of torus tanks that were used in launch vehicles that completed their mission showed that all of them are made of metal. It should be noted that composite materials have a significant advantage, they have a greater value of specific strength compared to metals. Unfortunately, composite torus tanks are being developed and exist only in experimental test samples. The advantage of torus tanks is the possibility of creating a compact layout of the launch vehicles. It is more rational to use them on the second or third stage and in booster orbiter of launch vehicles. The main calculated load case of the torus tank is the load due to internal pressure and the hydrostatic pressure of the liquid, increased by the calculated load during the movement of the launch vehicle. However, the use of composite torus tanks shows that the features of the geometry and the existing manufacturing technologies do not ensure the creation of uniformly strong structures. When loading a composite torus with internal pressure, the destruction occurs in the outer zone farthest from the axis of symmetry, although in a torus of constant thickness, the greatest stresses occur in the zone closest to the axis of symmetry [1].

The surface of the torus closest to the axis of symmetry has a large thickness of the composite layer due to the peculiarities of the geometry and winding technology. A distinctive feature of a composite tank is the need to take into account the requirements of hermeticity. Strength conditions do not always meet them. This feature leads to additional winding of 5-7 layers [2] or the use of combined linear structures. In this case, the hermeticity is provided by the metal liner, and the composite winding ensures required strength characteristics. For linear structures, it is not necessary to use a continuous composite winding over the entire surface of the torus. To create an equal-in-strength structure, it is advisable to apply a winding technique that allows to obtain isogrid reinforcement rather than a continuous longitudinal-transverse approach.

At the same time, it is necessary to take into account factors that affect the performance of such torus shells, namely: ensuring the hermeticity of the container, along with technological limitations during production.

Composite materials have high gas permeability so that gas leaks occur already at a pressure value of 10-15% of the nominal [2]. Therefore, to ensure the performance of such a shell, a sealing layer (combined shell) is used. It can be a metal liner or sealing films made of glass and polymers.

Use as a sealing layer of metal provides the following advantages: the sealing shell is a carrier, that is, it receives part of the force; the problem of placing and fastening internal-packing devices is solved; increased temperature range of application.

A condition of continuous winding of the tape is the main technological limitation during torus shells production.

## TASKS AND OBJECTIVES

Based on the above, the purpose of this work is to consider torus shells that are loaded with internal pressure and used in real projects as a comparison. These design variants are compared with combined torus tanks that have an isogrid composite reinforcement which is created due to longitudinal-transverse winding (LTW). The liner ensures the hermeticity of the shell and also absorbs some of the meridional and annular forces. Therefore, it is possible to formulate the purpose, object, subject, and tasks of the research.

The purpose of the study: to determine the parameters of a workable combined torus tank with isogrid composite reinforcement using the engineering method of calculation of the structure following with assessment of the mass characteristics with further comparison with “prototype” design variants.

Research object: combined torus shell with the composite isogrid reinforcement.

Research subject: Determination of advantages and disadvantages of the proposed combined torus tank structures in comparison with the known used design options.

Tasks of research:

– based on a carried out review of existing metal structures of torus tank, select for comparison tanks with defined parameters of geometry, load conditions and used materials;

– determine parameters and weight of the combined tanks with prototypes load conditions with the use of the engineering method of calculating the efficient torus tank with isogrid composite reinforcement;

– based on the results of the numerical analysis, draw a conclusion about the expediency and effectiveness of using combined torus tanks with isogrid reinforcement in comparison with metal prototypes.

## MATERIALS AND METHODS

All metal torus tanks selected for comparison are tanks for storing the working fluid of the turbo-pump unit (TPU). Water is used as the working fluid. The following containers are selected:

- PS2WT tank of the second stage of the Indian launch vehicle PSLV;
- L-33WT tank of the second stage of the European launch vehicle Ariane-1, 2,3;
- L-140WT tank of the first stage of the European launch vehicle Ariane-1, 2,3;
- L110WT tank of the 1st stage of the Indian launch vehicle GSLV Mk3.

All torus tanks are designed to store water that is used both for cooling the hot gas produced in the gas generator for pressurizing the fuel tanks and the water tank, and also for cooling the bearings of the NDMG pump on the TPU shaft [3 - 5]. Tank parameters, physical and mechanical characteristics of materials used, geometry and load conditions are given in Tables 1-3.

Carbon-carbon unidirectional composite UKN300 is used as a composite reinforcement material. Tape thickness 0.1 mm, width 10 mm, density 1750 kg/m$^3$, modulus of elasticity 220 GPa, relative elongation $\varepsilon = 1\%$. The composite reinforcement is isogrid in the meridional and circular directions. Moreover, taking into account the width of the tape, the circular winding of composite reinforcement is performed under the condition of maximum coverage of the inner surface of the torus. This condition ensures the maximum bearing capacity of the circular composite reinforcement.

The calculation of the geometry of the isogrid composite reinforcement is performed according to the engineering method. According to it, the composite reinforcement and the liner operate in the elastic zone. The liner seals the container, and the composite reinforcement provides strength. The total internal circumferentially distributed annular and meridional forces are distributed between the liner and the composite reinforcement. The conditions of compatibility of deformations are fulfilled between the liner and the composite reinforcement. The liner works under biaxial stress state conditions, and the composite tape under uniaxial stress conditions. The conditions of failure of composite reinforcement are determined according to the deformation theory of strength. The thickness of the liner for all combined tanks is taken as the minimum, which is determined by the technological limitations of manufacturing. In the work, the thickness value of 1 mm is accepted.

**Table 1 – Parameters of tanks selected for comparison**

| Tank name | Liquid, weight, (kg) | Material | Tank volume, (*l*) |
|---|---|---|---|
| PS-2WT | $H_2O$, 580 | AA6061-T6 | 685 |
| L-33WT | $H_2O$, 550 | AZ5G | 640 |
| L-140WT | $H_2O$, 2500 | 15CDV6 | 3730 |
| L-110WT | $H_2O$, 1558 | AA6061-T6 | 1850 |

**Table 2 – Physical and mechanical properties of materials**

| Material | Density, kg/m$^3$ | Modulus of elasticity, MPa | Strength limit, MPa | Yield strength, MPa |
|---|---|---|---|---|
| AZ5G [6] | $2.9*10^3$ | $7*10^4$ | 390 | 310 |
| 15CDV6 [7] | $7.8*10^3$ | $19*10^4$ | 1210 | 1150 |
| AA6061-T6 [8] | $2.7*10^3$ | $6.9*10^4$ | 310 | 270 |

**Table 3 – Geometry and working pressure of the tanks**

| Tank | Radius of the torus R, m | Distance from the axis of symmetry of the torus to the center c, m | Shell thickness, mm | Working load pressure, MPa |
|---|---|---|---|---|
| PS-2WT | 0.177 | 1.11 | 1.6 | 2.559 |
| L-33WT | 0.17 | 1.12 | 2.85 | 6.00 |
| L-140WT | 0.378 | 1.344 | 1.5*) | 0.9 |
| L-110WT | 0.25 | 1.5 | 2.4 | 2.705 |

*) – the thickness of the L-140WT tank is determined by the condition of supercharging with hot gases produced in the gas generator and cooled by water.

From the condition of equilibrium in the annular section of the torus, the required thickness of the meridional composite reinforcement $h_c^\beta$ is determined:

$$h_c^\beta = \frac{\pi \cdot P \cdot R^2 - E_л \cdot \left(\varepsilon_л^\beta - \mu_л \cdot \varepsilon_л^\alpha\right) \cdot \delta_л \cdot 2 \cdot \pi \cdot R}{E_c \cdot \varepsilon_c \cdot t_л \cdot n^\beta}$$

where P is the internal pressure of the torus, R is the radius of the cross section, $E_л$ is the modulus of elasticity of the liner, Ec is the modulus of elasticity of the composite, $\varepsilon_л^\beta, \varepsilon_л^\alpha$ are the relative elongations of the liner in the annular and meridional direction of the liner, $\mu_л$ is the Poisson ratio of the liner, $\delta_л$ is the thickness of the liner, $\varepsilon_c$ is the relative elongation of the composite, $h_c^\beta$ is the thickness of the composite reinforcement, $t_л$ is the width of the composite tape, $n^{\beta}$ is the number of meridional reinforcements. From the condition of equilibrium of the shell in the meridional section, we find the thicknesses of the composite reinforcement occurring in the annular section for the outer and inner radius of the torus. Figure 1 shows the distribution of internal forces for these radii.

**Figure 1 – Distribution of efforts in the torus tank in a meridional section**

In the case of uniform coverage of the inner equator of the torus, considering the width of the composite tape, the angle of inclination of the tape will be determined: $\psi = arctan\left(\frac{t^{\beta}}{4 \cdot R}\right)$, where $t^{\beta}$ is the specified value of the distance between the centers of gravity of two adjacent composite tapes on the inner equator taking into account tл. Since the longitudinal ring force is different on the outer and inner equators of the torus, the thickness of the circular reinforcement is determined by the condition of equilibrium at each equator.

The thickness $h_{\text{з}}^{\alpha}$ of the tape will be determined by the condition of equilibrium of the annular distributed force on the outer equator of the torus $R_0$:

$$h_{\text{з}}^{\alpha} = \frac{2 \cdot \pi \cdot R_0 \cdot \left(\frac{P \cdot R}{2} \cdot \left(\frac{2 \cdot c + R}{c + R}\right) - E_{л} \cdot \varepsilon_c \cdot (1 - \mu_{л}) \cdot \delta_{л}\right)}{E_c \cdot \varepsilon_c \cdot cos^2(\psi) \cdot t_{л} \cdot n^{\alpha}}$$

where n^α is the number of circular reinforcements, c is the distance from the axis of symmetry of the torus to the center of the cross section of the torus.

The thickness of the tape $h_{\text{в}}^{\alpha}$ is determined by the condition of equilibrium of the annular distributed force on the inner equator of the torus $R_{180}$:

$$h_{\text{в}}^{\alpha} = \frac{2 \cdot \pi \cdot R_{180} \cdot (\frac{P \cdot R}{2} \cdot \left(\frac{2 \cdot a - R}{a - R}\right) - E_{л} \cdot \varepsilon_{c} \cdot (1 - \mu_{л}) \cdot \delta_{л})}{E_{c} \cdot \varepsilon_{c}^{\alpha} \cdot cos^{2}(\psi) \cdot t_{л} \cdot n^{\alpha}}$$

Compare the thickness values obtained for the inner and outer equators and choose larger value for circular reinforcement.

The weight of the combined torus with isogrid composite reinforcement is determined as the sum weights of the liner and the mass of the composite reinforcement. The volume of the material and the mass of the liner are determined by the following ratios: $V_{л} = 2 \times \pi \times c \times 2 \times \pi \times R$, $M_{л} = V_{л} \times \gamma_{л}$, where $\gamma_{л}$ is the specific weight of the material.

The volume of the material and the mass of the longitudinal layer of the composite meridional reinforcement is determined by the ratios:

$$V_{2} = 2 \times \pi \times r_{i} \times t_{\text{к}} \times h_{\text{c}}^{\beta} ,$$

where $r_{i} = \sum_{y=1}^{n^{\beta}} \left(c + R \times cos\left(\frac{360 \cdot y}{n^{\beta}}\right)\right)$ is the radius of the tape support, and the mass is $M_{2} = V_{2} \times \gamma_{\text{к}}$

The volume of the material and the mass of the annular layer of the composite meridional reinforcement is determined by the ratios:

$$V_{1} = \frac{2 \times \pi \times R}{cos(\psi)} \times t_{\text{к}} \times n^{\alpha} \times h_{i}^{\alpha}, \quad M_{1} = V_{1} \times \gamma_{\text{к}}$$

Weight of combined torus tanks with isogrid composite reinforcement is calculated according to this engineering method. Weight of combined tanks with a continuous composite coating during longitudinal-transverse winding is determined according to the method given in the work [1].

## RESULTS

The results of comparing the weight of the original tank with the combined composite tanks with a continuous coating and isogrid reinforcement are shown in Table 4.

**Table 4 - Tanks weight comparison**

| Tank | Tank weight, kg | | |
|---|---|---|---|
| | Prototype | Composite reinforcement | |
| | | With continuous LTW coating | With isogrid LTW coating |
| PS2WT | 33.5 | 30.2 | 29.1 |
| L-33WT | 62.0 | 52.0 | 50.6 |
| L-140WT | 232.8 | 196.4 | 185.3 |
| L110WT | 95.9 | 73.9 | 73.4 |

The analysis of the obtained results shows that using combined composite torus tanks instead of metal ones significantly reduces the weight of the tanks. Applying composite continuous coatings on the torus surface reduces the tank's weight by 9-22 percent. Using isogrid composite coatings reduces the weight of the prototype tanks by 13-23.5 percent.

## SUMMARY

Based on the results of the work, the following conclusions can be drawn:

1. To design torus tanks of minimum weight, it is advisable to perform them combined. In this case, the metal liner performs the hermetic function, and the composite winding ensures necessary strength.
2. The thickness of the liner should be as minimal, taking into account the technological requirements of production. The use of additive technologies makes it possible to make liner thinner.
3. For composite linear structures, it is not necessary to use continuous composite winding over the entire surface of the torus. The design options with isogrid reinforcement ensure the workability of the construction while enhancing weight characteristics by 13-23.5%.

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