COMPOSITE IRREGULAR LATTICE SHELLS DESIGNING FOR SPACE APPLICATIONS

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SUMMARY

For the last years the Khrunichev Space Center has developed cylindrical and conical carbon fiber reinforced plastic (CFRP) lattice shells successfully used as part of the "Proton-M" launch-vehicle (LV), "Breeze-M" upper stage and "Express-MD1" spacecraft (SC). The paper studies the methodology of CFRP irregular lattice shells designing. The use of irregular lattice structure is explained by applying the concentrated longitudinal loads to end faces of structure.

Keywords: Lattice structure, Regular and irregular structure of lattice shell, Launch-vehicle (LV), Spacecraft (SC), Finite element model (FEM), Optimal designing.

INTRODUCTION

Due to the necessity to improve the load-bearing capacity of LV and to reduce the mass of SC framework, the Khrunichev Space Center has developed a series of CFRP lattice compartments. The examples of such compartments are: conical adapters for mounting heavy spacecraft with mass of up to 7 t on "Breeze-M" Upper Stage (Figures 1 and 2), cylindrical interstage compartment of the "Proton-M" LV (Figure 3), and load-bearing bodies of spacecraft like "Express-MD1" SC (Figure 4).

CFRP lattice compartments and their classification

Reviewed are the conical and cylindrical lattice compartments which consist of spiral ribs system at + α and – α angles to generating lines of compartments and circular ribs.

Some compartments, for example, interstage compartments of the "Proton-M" LV, have thin non-load-bearing skin.

The CFRP lattice shells used at present can be classified by two criteria: regularity of lattice and presence of skin (Table 1).

Table 1.Classification of lattice structures for space applications

Regularity of lattice structure	Presence of shell	
	without skin	with skin
regular	SC adapters with clamp band-type separation system (Figure 1)	LV interstage compartments (Figure 3)
irregular	SC adapters with separation system as local pyrolocks (Figure 2). Bodies of spacecraft with separation system as local pyrolocks (Figure 4)	-

CFRP regular lattice compartments

The methods of designing of CFRP regular lattice shells are presented in papers [1], [2]. The following parameters are variable when optimizing the structure of these shells: inclination of spiral ribs to generating line; distance between spiral ribs; dimensions of cross-sections of spiral and circular ribs; amount and location of circular ribs.

CFRP IRREGULAR LATTICE COMPARTMENTS DESIGNING

The CFRP irregular lattice compartments emerged due to necessity for compartment structures to bear high concentrated longitudinal loads on structure end faces.

In this paper we shall study these compartments from the following conditions:

- distance between load points on interface of compartment is same;
- number of load points on upper and lower end faces is same;
- angular shift of load points on lower interface compared upper interface is angle two times as less angular distance between load points on upper interface of compartment.

The angular distance between spiral ribs of irregular lattice structure is uneven: the distance in area of concentrated loads is two-three times as less. The examples of these shells are: lattice adapter for spacecraft developed on base of the Boeing 702 platform (Figure 2) and lattice framework of “Express-MD1” SC (Figure 4).

The experience in designing these compartments showed that the following designing sequence is required to find optimal parameters of compartment structures:

1) Finding of spiral rib inclinations to generating line;
2) Finding of set of allowed distance between spiral ribs in reinforced areas of the structure and in areas with regular lattice;
3) Finding of width of reinforced area and mounting of fitting;
4) Finding of number and position of circular ribs;
5) Finding of optimal mass of lateral rib cross-sections using finite element simulations for all structure options considering strength and stiffness limitations;
6) Checking refined finite element simulations of shell strength and stiffness.

Let us review in detail each of these phases.

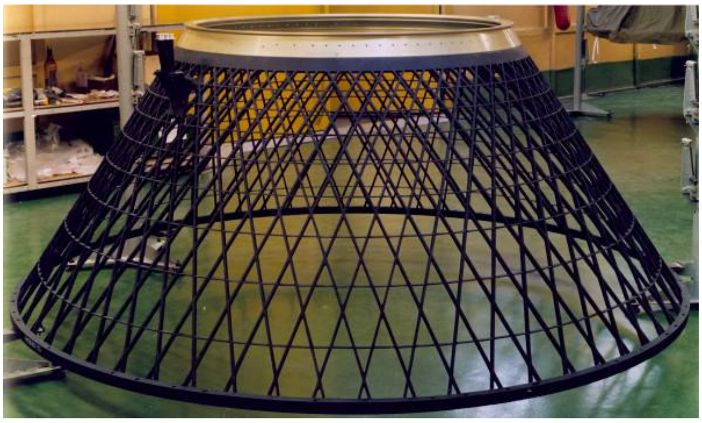


Fig. 1. Lattice adapter for SC with band-type separation system

Fig. 2. Lattice adapter for SC with discrete separation system

Fig.3. Equipment compartment of “Proton-M” LV Stage II

Fig. 4. Load-bearing lattice cylinder of SC in tandem injection pattern

Finding of spiral ribs' inclination to generating line

Let draw a conventional spiral rib (geodetic line) to connect loading point on upper cross-section with the nearest point on lower cross-section. Inclination of this conventional spiral rib to generating line is taken as inclination of spiral ribs. The allowed inclination of spiral rib to generating line is usually in the range of 10-35 angular degrees. If selected angle is beyond the allowed values, we should try to draw a conventional spiral rib to connect another pair of points. A situation can exist when it is impossible to draw a spiral rib within the allowed inclination. In this case the lattice structure will rather be inefficient.

Finding of set of allowed distances between spiral ribs in reinforced areas of structure and in regular lattice areas

Let define set $\Phi = \{\varphi_1, \varphi_2, ...\}$ as set of technologically feasible angular distances between spiral ribs. Let n be a number of similarly inclined spiral ribs of lattice structure, then

$$\begin{cases} \varphi_n \in \Phi, \text{ if } (360/n)\cdot 100 \in I, \text{ where I - is set of integer numbers}, \quad (1) \\ \varphi_n \notin \Phi, \text{ in a contrary case.} \end{cases}$$

Coefficient "100", used in the formula, allows estimating the angular distance between spiral ribs with accuracy of up to hundredth fractures of degree. Let write the set of allowed angular distance between of spiral ribs derived from formula (1):

$$\Phi = \{...;(3^{\circ})_{120};(3.6^{\circ})_{100};(3.75^{\circ})_{96};(4^{\circ})_{90};(4.5^{\circ})_{80};(4.8^{\circ})_{75};(5^{\circ})_{72}; (6^{\circ})_{60};(7.2^{\circ})_{50};(7.5^{\circ})_{48};(8^{\circ})_{45};(9^{\circ})_{40};(10^{\circ})_{36};(11.25^{\circ})_{32};(12^{\circ})_{30};(14.4^{\circ})_{25};(15^{\circ})_{24};\ldots\}.$$

By laying the number of spiral ribs in abscissa axis and angular distance in ordinate axis we can graphically represent the "Φ" set (Figure 5). The real structures implement a very small part of "Φ" set elements; this part is shown in dark solid dots in Figure 5.

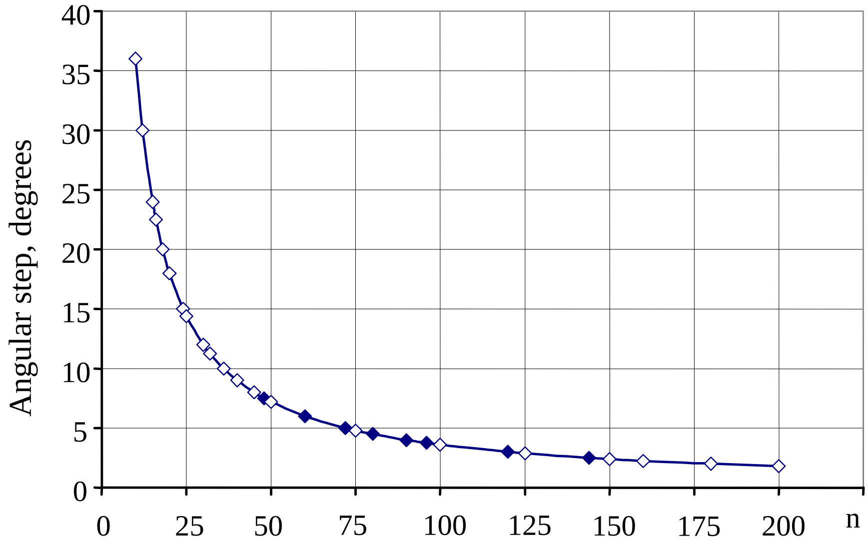


Fig. 5.

The next step is an implementation of additional spiral ribs in reinforced lattice areas. Let's introduce a condition: distance between additional spiral ribs shall be divisible by distance between ribs in main lattice. For each φ_i of Φ, set F={φ_1, φ_2,...} is possible according to the following rule:

$$\begin{cases} f_k \in F, \text{ if } ((\varphi_i/k)\cdot 100) \in I, \text{ where I – is set of integer numbers,} \\ f_k \notin F, \text{ in a contrary case.} \end{cases} \quad (2)$$

where k is number of additional ribs between the ribs in reinforced areas of main lattice. For example, for n=48 and φ_{48}=7.5, set F = {..., $(1.25)_5$, $(1.5)_4$, $(2.5)_2$, $(3.75)_1$}. The minimum angular spacing between both regular and additional spiral ribs is defined by structure overall dimensions and by technological feasibility.

Concerning upper and lower compartment end faces, we know the required quantity of reinforced areas. It is defined by number of bolts or separation locks, and by structural properties of adjacent compartments. To simplify tests and simulation of the compartment we'll put a condition that lattice structure near reinforced areas at end faces should be the same. This can be reached if only number of similarly inclined spiral ribs is divisible by number of reinforced areas on each interface. Thus, defined is the allowed subset Φ^m of set Φ, where m – is a number of bolts or joint locks, then

$$\begin{cases} \varphi_n \in \Phi^m, \text{ if } (n/m) \in I \text{ where I – is set of integer numbers,} \\ \varphi_n \notin \Phi^m, \text{ in a contrary case.} \end{cases} \quad (3)$$

The examples are below:

$$m=4: \quad \Phi^4 = \{...;(3^\circ)_{120};(3.6^\circ)_{100};(3.75^\circ)_{96};(4.5^\circ)_{80};(5^\circ)_{72}; (6^\circ)_{60};(7.5^\circ)_{48};(9^\circ)_{40};(10^\circ)_{36};(11.25^\circ)_{32};(15^\circ)_{24};\ldots\}.$$

$$m=8: \quad \Phi^8 = \{...;(3^\circ)_{120};(3.75^\circ)_{96};(4.5^\circ)_{80};(5^\circ)_{72}; (7.5^\circ)_{48};(9^\circ)_{40};(10^\circ)_{36}; (11.25^\circ)_{32};(15^\circ)_{24};\ldots\}.$$

Two options of uneven loading on compartment end faces are possible:

Option 1 – loads are applied on compartment only in “point” zones both in case of compression and in case of tension.

Option 2 – only tensile loads are applied in “point” zones, the compression is propagated along entire interface circumference.

It is significantly (up to 5 times) profitable for Option 1 to decrease the distance between spiral ribs in loaded area, as the remaining spiral ribs of the structure are practically not loaded. For designing of the compartment, it is necessary to select an option from Φ^m set with maximum distance between spiral ribs, at which the connectivity of structure spiral ribs remains. In practice, the final option with minimum number of spiral ribs’ intersections will not be rather optimal. To reduce the designing duration we should start to review the options of lattices with a spiral rib intersecting 4-5 of other spiral ribs.

As the first approximation for Option 2 it is advisable to select parameters of regular lattice structure evenly loaded with equivalent loads. Then, it is necessary to select the most approximate option from Φ^m set with even or larger distance between spiral ribs.

A number of requirements for attaching devices and equipment to lattice ribs are made in the real structures. These requirements define some limitations to allowed distances between spiral ribs in regular lattice and reduce a number of options that require analysis to select the optimal one.

Finding of reinforced area width and mounting of fitting

For each element of Φ^m set estimated at Phase 2 we define:

- position of regular lattice ribs relative to fitting mounting areas; the aim is optimal integration of fitting in lattice structure;

- number of additional spiral ribs in reinforced area of structure, namely, in loaded area.

- selection of position of additional ribs relative to ribs in regular lattice.

In process of fitting mounting designing, inclination of spiral ribs can be corrected within 1-2 degrees.

Finding of position of circular ribs

The circular ribs are arranged in the middle between intersecting spiral ribs. This arrangement of circular ribs is allowed with no limitation to dimensions of lattice cell or any other requirements.

Finding of optimal mass of lateral rib cross-sections using finite element simulations for all structure options considering limitations to stiffness and strength

The optimal lattice compartment option is selected from the derived ones. For this, it is necessary to determine cross-sections of spiral ribs. In case of designing the stiffness (with valid stiffness limitation) it is performed on based on elementary engineering calculations. While designing the buckling and strength the following algorithm is used: a certain width of spiral ribs is given. The height of spiral ribs is selected by MSC.NASTRAN optimization algorithm SOL200 (selection of minimum mass). The buckling and strength limitations are also taken into account. The MSC.NASTRAN solution gives not only height of intersection, but mass of the structure. The solutions are found for several widths of spiral ribs. Plotted are diagrams of structure mass depending on width of spiral ribs for each lattice option. Thus, the optimal option of lattice structure is selected.

Checking refined finite element simulations

The strength of lattice compartment is estimated per complex criteria. The buckling load of compartment is estimated with account of geometrical non-linearity. If required, the width of reinforced area is little increased or decreased, additional circular ribs are introduced, and dimensions of ribs cross-sections and reinforcements under fittings are corrected.

EXAMPLE OF DESIGNING OF IRREGULAR LATTICE STRUCTURE

Let us study the designing of irregular lattice structure taking the load-bearing cylinder of SC in tandem injection pattern as an example [3]. The cylinder layout is shown in Figure. 6. Each interface has 8 locks (areas of load transfer). Upper locks are displaced relative to lower locks by 22.5 degrees.

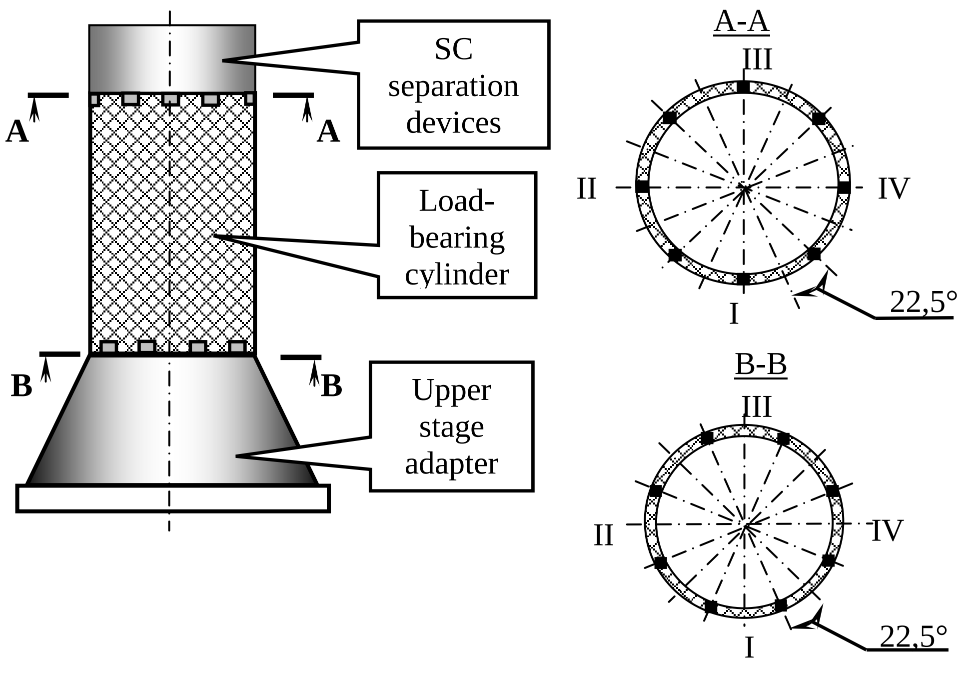


Fig. 6. Cylinder load-bearing interfaces

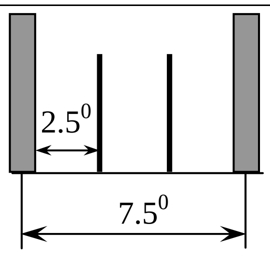
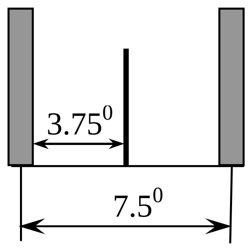
Table 2. Possible options of lattice structures

n/m			2	3	4	5	6
Total number of ribs (2·n)			32	48	64	80	96
Regular angular step (φ_n)			22.5°	15°	11.25°	9°	7.5°
Angular step of additional ribs (f_k)	Additional ribs, pcs.	k=1	11.25°	7.5°	-	4.5°	3.75° 1)
		k=2	7.5°	5°	3.75°	3°	2.5° 2)
		k=3	-	3.75°	-	2.25°	
		k=4	4.5°	3°	2.25°		
		k=5	3.75°	2.5°			

Let us preliminary define inclination of spiral ribs. For this, let draw a geodesic line from upper lock to nearest lower lock. For the given cylinder dimensions, inclination will be 14.2 degrees.

The acceptable distances between spiral ribs of regular and irregular lattices are shown in Table 2. Possible options of reinforcing for one of acceptable regular lattice structure are shown in Table 3. Selection of this option for further studying was stipulated for requirements to equipment arrangement because the lattice structures with rare grid are difficult to attach the equipment.

Table 3. Options of reinforcement

 1) Regular lattice - 96 ribs. Additional ribs - 32 pcs. In total - 128 ribs.	 2) Regular lattice - 96 ribs. Additional ribs - 16 ribs. In total - 112 ribs.

The resulted lattice structures are shown in Figure 7. This structure has double circular ribs misaligned from spiral ribs' intersections. This option of circular ribs arrangement makes easier the attaching of equipment to the lattice.

Figure 8 shows the mass of different lattice structures as function of width of spiral ribs. Figure 8 demonstrates that for this compartment the irregular lattice is optimal with one pair of additional spiral ribs in area of each fitting.

Figure 9 shows the form of lattice cylinder buckling. The calculation is performed with the help of the detailed finite-element cylinder model developed in MSC.NASTRAN. Also Figure 9 shows the destruction of cylinder during the tests. The developed methods of lattice structure simulations allow predicting the test results with accuracy of 10%.

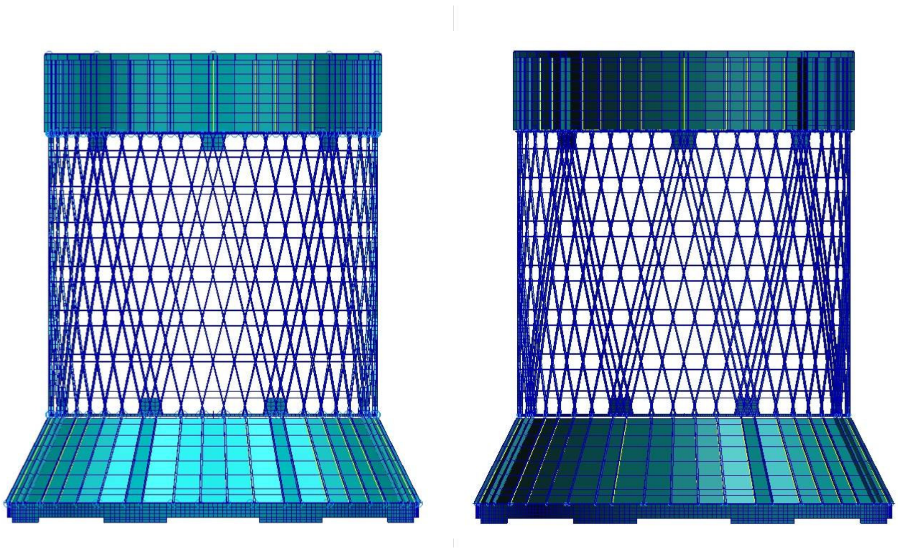


Fig.7. Types of lattice adopted for further development (FEM)

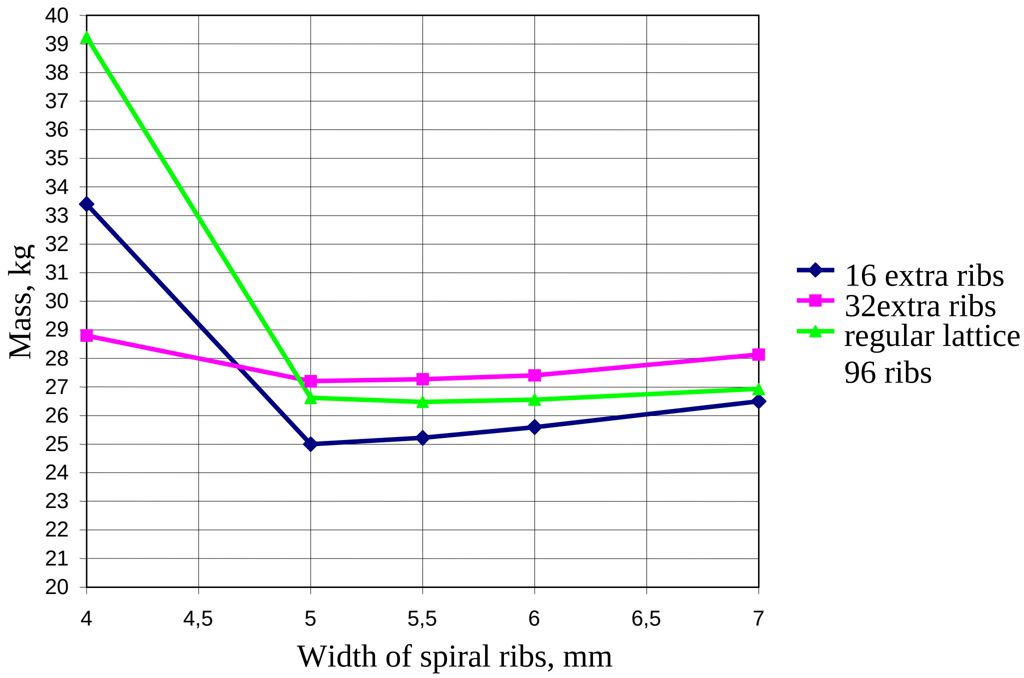


Fig. 8. Mass of cylinder as function of width of spiral ribs

CONCLUSION

The paper gives the description of designing of CFRP conical and cylindrical irregular lattice compartments. The proposed method allows to design the composite lattice compartments with highly weight saving. Concerning the reviewed example of cylindrical lattice compartment, the mass was decreased by 40% compared the prototype. The compartment prototype is metal stringer cylinder.

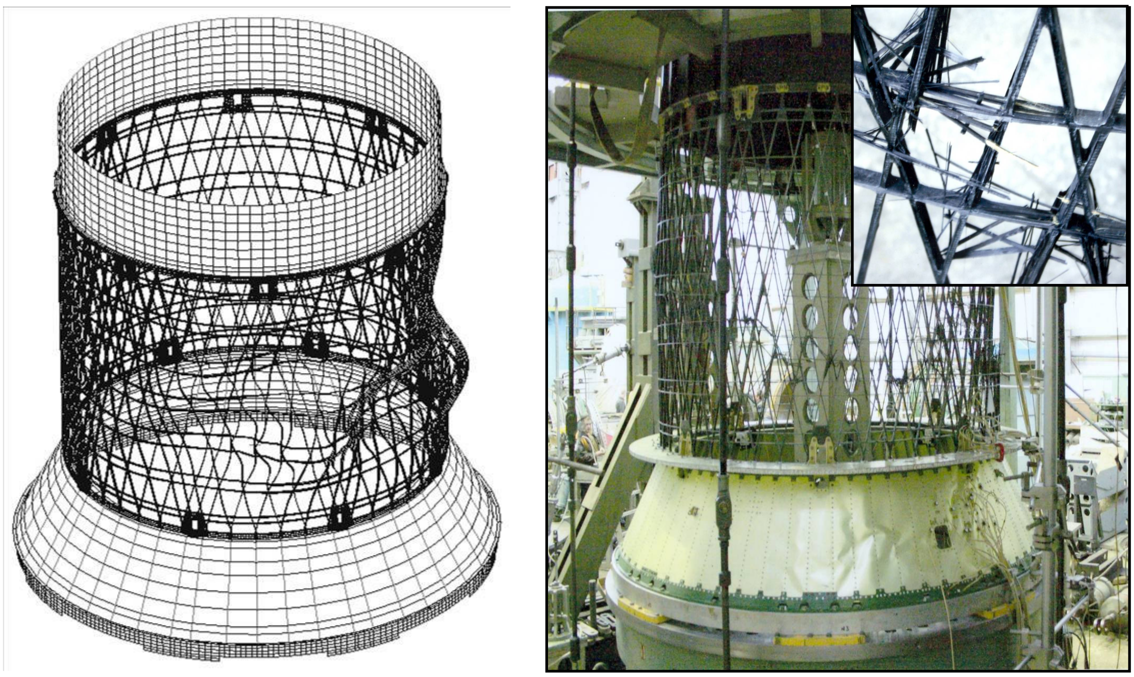


Fig. 9.

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