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# Structural Optimization Approach for Specially Shaped Composite Tank in Spacecrafts

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## Abstract

This study proposes an optimized approach of designing in which a finite element model of the specially shaped composite tank for spacecrafts is built by applying the finite element analysis. The composite layer is preliminarily designed by combining the quasi-network design method with numerical simulation, which determines the ratio between the angle and the thickness of the layer as the initial value of the optimized design. By adopting the adaptive simulated annealing algorithm, the angles and numbers of layers at each angle are optimized to minimize the weight of structure. Based on this, the stacking sequence of composite layers is formulated according to the number of layers of each angle in the optimized structure by applying the enumeration method and combining the general design parameters. Numerical simulation is finally adopted to calculate the buckling limit of tanks in different designing methods. This study takes a composite tank with a cone-shaped cylinder body as example, in which ellipsoid head section and outer wall plate are selected as the object to validate this method. The result shows that the quasi-network design method can improve the design of composite material layer in tanks with complex preliminarily loading conditions. The adaptive simulated annealing algorithm can reduce the initial design value of weight by 30%, which effectively probes the global optimal solution and optimizes the weight of structure. It can be therefore proved that, this optimization method is capable of designing and optimizing specially shaped composite tanks with complex loading conditions.

*Keywords:* Specially shaped composite tank; Finite Element Analysis; Optimal design; Quasi-network design method; adaptive simulated annealing algorithm

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## 1. Introduction

Composite materials are widely adopted in aeronautics and astronautics, watercrafts, architecture and ordnance industry because of their high specific strength, high specific modulus, favorable designability and low cost [1]. One specific application of composite material is the design of pressure containers [13-14]. Different kinds of pressure containers are used in aeronautics and astronautics to store liquids and gases, exemplified by surface tension propellant tanks and gas cylinders for spacecraft propulsion system. Compared to traditional metal tanks, the pressure containers with composite material have lighter body, higher stiffness and stability, better fatigue resistance, favorable designability and lower cost [2], which attracts more attentions in recent developments of aircraft designs.

The shape of tank for spacecrafts is primarily designed based on the structural and functional requirements of spacecrafts. Differences in functions can lead to the variance of morphologies in tanks. Traditional tanks are mainly spherical,

requirements of advanced craft design, specially shaped tanks are more widely used in spacecrafts nowadays. Because of the irregularity, it is difficult to apply traditional analytical design method of regular tanks in the design of specially shaped tanks. The design approach for irregularly shaped tanks should be an optimization of the conventional analytical methods by substituting the analytical solutions by advanced numerical modeling results to ensure the reliability and economic efficiency of the design [3].

In the process of designing specially shaped composite tank for spacecrafts, the shape, material and loading conditions are defined according to the requirements of task design. The thickness and initial value of angles of different parts in the tank are determined by adopting finite element method (FEM) to develop the numerical model, the quasi-network design method (QNDM) and the combination of FEM and this QNDM. The tank will be finally optimized to reduce its weight and increase the buckling limit.

## 2. Model Details

The total height of inner part of the tank is 1800mm, the diameter of the front end is 900mm, and the diameter of the rear end is 1500mm. The major semi axes of the ellipsoids of the

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cylindrical or ellipsoidal. However, based on the new re-

front, middle and rear are 500mm, 525mm and 580mm respectively, and the ratio between the major and minor semi axis is 1.6:1. The thickness of metallic liner is 1.5mm, and the thickness of each layer of the composite material is 0.2mm. There are connection frames on the upper and lower end of the tank, whose length is 200mm. Fig. 1 shows the FE model of the composite tank, which is developed on the commercial platform of ANSYS .

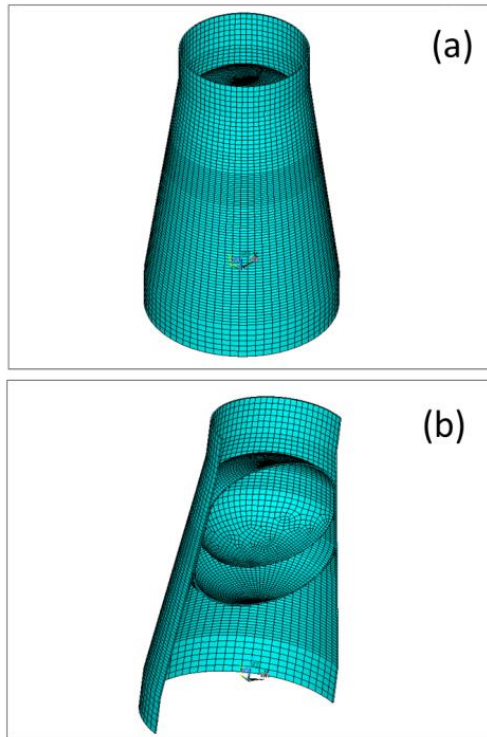


Fig. 1. Finite element model of tank  
(a) 1/2 finite element model (b) the whole finite element model

The metallic liner and the connection frames are applied with the element of SOLID 95, and the layers of composite material adopted are of SOLID 46 element. The properties of metallic liner and composite material are provided in Table 1 and Table 2, and the material positions can be found in Fig. 2. The loading condition of the tank is relatively complex, with the upper surface of the connection frame receiving axial force, shearing force and bending moments, and the internal surface of certain part (i.e. the internal surface of RJ part) receiving internal pressure. In the FE model, the circumference of each part (for the ellipsoids, their latitude line) is in X direction, i.e. the  $0^\circ$  direction of the composite material layer. The generatrix direction (for the ellipsoids, their longitudinal line) is in Y direction, i.e. the  $90^\circ$  direction of the composite material layer.

Table 1. Material property of metallic liner

Young's modulus (GPa)	68.2
Poisson's ratio	0.3
Yield Strength (MPa)	350
UTS (MPa)	441
Density ( $\text{kg}\cdot\text{m}^{-3}$ )	2840

Table 2. Property of composite material

Young's modulus $E_{11}$ (GPa)	125.4
Young's modulus $E_{22,33}$ (GPa)	9.4
Shear modulus $G_{12,13,23}$ (GPa)	4.1
Poisson's ratio $\nu_{23}$	0.329
Poisson's ratio $\nu_{12,13}$	0.025
UTS (MPa)	971
Density ( $\text{kg}\cdot\text{m}^{-3}$ )	1500

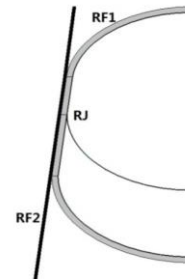


Fig. 2. The figure of the material position

### 3. Design of Composite Layer by QNDM

As the composite tank is specially shaped, and the loading condition is complex, the 'network theory' method applied in conventional filament-winding inner-pressure vessels cannot be adopted to define the thickness and laying angle. The preliminary design can be realized by combining the quasi-network design method and numerical modelling techniques, such as FEM.

#### 3.1 QNDM

The QNDM is also called stress ratio design method [4-5]. We take the example of filament winding design method to explain the process of QNDM. Based on the requirement of the conformance of the direction of filaments and the loading, only the bearing capacity of composite material is taken into account, leaving out the stiffness and strength of the structure, and distributing the number of filaments of each layer according to the primary stress of the internal surface, thus determining the ratio of the number of layers of each direction. The specific process is as follows:

(1) Calculating the stress: Calculate the stress of the laminated boards  $\sigma_x$ ,  $\sigma_y$ ,  $\sigma_{xy}$  according to the properties of the boards of each direction; obtain the ratio of stress,  $\sigma_x$ :  $\sigma_y$ :  $\sigma_{xy}$ :  $1$ :  $a$ :  $b$ .

(2) Determining the ratio of the number of layers of each direction: set the angles as  $0^\circ$ ,  $90^\circ$ , and  $\pm 45^\circ$  based on the directions of stress, and correspond  $\sigma_x$ ,  $\sigma_y$ , and  $\sigma_{xy}$  to the layers of  $0^\circ$ ,  $90^\circ$ , and  $\pm 45^\circ$ . Make the number of layers (the ratio of layers of each direction) conform to the ratio:  $n_{0^\circ}$ :  $n_{90^\circ}$ :  $n_{\pm 45^\circ}$ :  $1$ :  $a$ :  $2b$ .

(3) Calculating the stress again: Analyze the stress according to the laminated board determined above, and obtain the corresponding stresses  $\sigma'_x$ ,  $\sigma'_y$ , and  $\sigma'_{xy}$ .

(4) Differentiating the deviation of stress ratio: Compare  $\sigma'_x$ ,

$\sigma_y'$ , and  $\sigma_{xy}'$  with the original stress ratio  $1: a: b$ . Given that the deviation is within the permissible range (take 5%), the result can be adopted; otherwise determine a new ratio of layers in accordance with the new stress ratio until the deviation gets into the permissible range.

**3.2 Ratio of the number of composite layers**

As the internal stiffness of composite laminated boards are only related to the layer angles and the ratio of layer numbers irrelevant to the sequence of the layers, after setting the angles  $0^\circ$ ,  $90^\circ$  and  $\pm 45^\circ$  one only needs to determine the ratio of layer numbers [6]. In accordance with the QNDM, calculate the stresses of the sidings of each part  $\sigma_x$ ,  $\sigma_y$ , and  $\sigma_{xy}$  based on the properties of each direction and the numerical simulation based on FEM, and obtain the stress ratio  $\sigma_x: \sigma_y: \sigma_{xy}=1: a: b$ . The initial values of the layers in each part can be found in Table 3. The following iterating results are all the largest stress of the results of the finite element calculation.

Table 3. Initial value of composite material parameters of each part of the structure

Position	RF1	RF2
Number of layers	8	8
Layer Angle	$[0/\pm 45/90]_s$	$[0/\pm 45/90]_s$
Thickness of single layer (mm)	1.0	1.0
Total Thickness (mm)	8.0	8.0

The results combining the data on Table 3 and the calculation of ANSYS are shown on Table 4.

Table 4. The computed result of the first iteration

Position	RF1	RF2
$\sigma_x$ (MPa)	40.999	33.687
$\sigma_y$ (MPa)	653.358	304.086
$\sigma_{xy}$ (MPa)	5.116	7.396
$\sigma_x:\sigma_y:\sigma_{xy}=1:a:b$	1.000:15.936:0.125	1.000:9.027:0.220
$n_0:n_{90}:n_{\pm 45}=1:a:2b$	1.000:15.936:0.250	1.000:9.027:0.440

Recalculate the structure according to the layer number ratio on Table 4, obtain the corresponding stress of each part  $\sigma_x'$ ,  $\sigma_y'$ , and  $\sigma_{xy}'$ , and differentiate the deviation of stress ratio. The parameters of second iteration of composite material are provided in Table 5, and the calculated results are on Table 6.

Table 5. Composite material parameters of the second iteration

Position	RF1	RF2
Number of layers	4	4
Layer Angle	$[0/90/45/-45]$	$[0/90/45/-45]$
Thickness of single layer (mm)	1.000/15.936/0.125/0.125	1.000/9.027/0.220/0.220
Total Thickness (mm)	17.186	10.467

Table 6. The computed result of the second iteration

Position	RF1	RF2
$\sigma_x$ (MPa)	1354.690	643.027
$\sigma_y$ (MPa)	583.309	192.386
$\sigma_{xy}$ (MPa)	535.190	181.269
$\sigma_x:\sigma_y:\sigma_{xy}=1:a:b$	1.000:0.431:0.395	1.000:0.299:0.282
$n_0:n_{90}:n_{\pm 45}=1:a:2b$	1.000:0.431:0.790	1.000:0.299:0.564

After six times of iterations, the deviation of stress ratio is lower than 5%. The trends of value  $a$  (the ratio of  $90^\circ$  layer) and value  $b$  (the ratio of  $\pm 45^\circ$ ) in accordance with the increasing number of iteration are displayed in Fig. 3, and the final results are given in Table 7.

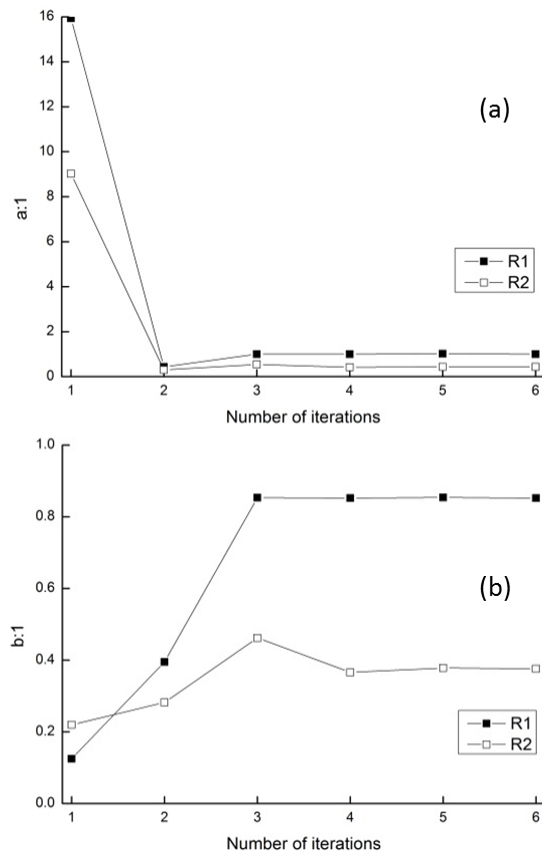


Fig.3. Variation trend of the value “a” and “b” in every part of structure with the iteration times increasing  
(a) Variation trend of the value “a” with the iteration times increasing  
(b) Variation trend of the value “b” with the iteration times increasing

Table 7. The final iteration result

Position	RF1	RF2
$\sigma_x$ (MPa)	237.015	208.606
$\sigma_y$ (MPa)	237.034	90.398
$\sigma_{xy}$ (MPa)	201.905	78.487
$\sigma_x:\sigma_y:\sigma_{xy}=1:a:b$	1.000:1.000:0.852	1.000:0.433:0.376
$n_0:n_{90}:n_{\pm 45}=1:a:2b$	1.000:1.000:1.704	1.000:0.433:0.752

According to Table 7, when the layer angles are  $0^\circ$ ,  $90^\circ$ , and  $\pm 45^\circ$ , the approximate value of layer number ratio of each

angle is  $n_0:n_{90}:n_{\pm 45}=1:1:1.7$ . For the convenience of pavement, take  $n_0:n_{90}:n_{\pm 45}=1:1:1.8$ ; the layer number ratio of the external boards is approximately  $n_0:n_{90}:n_{\pm 45}=1:0.4:0.8$ . Thus the initial values of the optimized design of the composite material layers are shown on Table 8.

Table 8. Initial parameters value of laminate composite optimization design in every part of the structure

Position	RF1	RF2
Number of layers	8	8
$n_0:n_{\pm 45}:n_{90}$	1:1.8:1	1:0.8:0.4
Number of $0^\circ$ layer	40	20
Number of $\pm 45^\circ$ layer	72	16
Number of $90^\circ$ layer	40	8
Total number of layers	152	44
Thickness of single layer (mm)	0.2	0.2
Total Thickness (mm)	30.4	8.8

#### 4. Structural Optimization of Laminated Structure

The optimization of laminated structure in specially shaped composite tank can be divided into two procedures [9]: firstly, take the layer parameters of Table 8 as the initial parameters, integrate them with the optimization package (Isight) and FEM software (Ansys) and optimize the design of composite layers by applying the ASA with the target of minimizing the weight of the structure to define the number of layers of each direction. Secondly, select the best sequence of paving layers to enlarge the buckling limit of the structure [7-8].

The tank for spacecrafts is designed according to the stiffness, and then its strength is calibrated. The allowable strain for the design of the filament direction of composite material is  $4500\mu\epsilon$  [4]. The allowable value for the design of stress of filament direction is obtained through the material strength limit divided by the safety factor 1.5, which results in 647MPa. The allowable value for the design of stress of metallic liner Mises is 441MPa.

##### 4.1 Sub-step 1: minimizing the weight of the structure

Every part of the specially shaped composite tank, because of its complex loading condition, is expected to meet the requirements of the allowable values in stiffness and strength. The mathematic model of the optimization problems can be presented as:

$$X=\{ANG1, ANG2, R1_0, R1_{ANG1}, R1_{90}, R2_0, R2_{ANG2}, R2_{90}\}$$

$$\text{Min: } f(X)$$

$$\text{s.t. : } R1STRAIN, R2STRAIN \leq 0.0045$$

$$R1STRESS, R2STRESS \leq 647$$

$$RJSEQV \leq 441$$

$$15 \leq ANG1, ANG2 \leq 75$$

The designing variables are the layer angle of structure RF1

saving  $0^\circ$  and  $90^\circ$ -ANG1, the layer number of  $0^\circ$ -R1<sub>0</sub>, the layer number of (ANG1)<sup>°</sup>-R1<sub>ANG1</sub>, the layer number of  $90^\circ$ -R1<sub>90</sub>; the layer angle of structure RF2 saving  $0^\circ$  and  $90^\circ$ -ANG2, the layer number of  $0^\circ$ -R2<sub>0</sub>, the layer number of (ANG2)<sup>°</sup>-R2<sub>ANG2</sub>, and the layer number of  $90^\circ$ -R2<sub>90</sub>. The objective of optimization is to minimize the weight of the structure. In the constraint conditions, R1STRAIN and R2STRAIN represent the maximum strains of single filament direction of RF1 and RF2 respectively, R1STRESS and R2STRESS represent the maximum stresses of single filament direction of RF1 and RF2 respectively, and RJSEQV is the maximum stress of metallic liner Mises.

The ASA is an overall optimization algorithm. The early-stage Simulated Annealing (the SA) was proposed by Metropolis *et al.* [12], which analogizes the combinational optimization problem and the thermal balance of statistic mechanics through simulated annealing, generates new design point from the original design point through variation, and finally verges into the global optimal solution. The SA algorithm succeeded in solving the combinational optimization problem of discrete variables and the minimization problem of continuous variable function. The ASA is an optimized algorithm put forward by Ingber *et al.* [10], which has a better performance in global optimal solution than the conventional SA algorithm. The advantages of ASA algorithm include: capability of dealing with arbitrary system and objective function; capability of probing the global optimal solution; being suitable for continuous and discontinuous design spaces; and being applicable in dealing with real and discrete variables. These advantages make the ASA algorithm suitable for solving optimization problems of composite material laminated boards. However, due to its repetitive cycle of annealing process of ASA, the optimization is relatively slow, which makes it less efficient. Therefore it is not the fastest algorithm.

The finite element calculation of the specially shaped composite tanks is conducted by the Ansys Parametric Design Language (the APDL) approach. The optimization process is realized by integrating Ansys and Isight. The parameters of ASA are set as follows: the discrete value of maximum iteration is 1000; the maximum difference value between the feasible solution of each execution and the current optimal solution is  $1.0 \times 10^{-8}$ ; the relative ratio of the decreasing temperature parameter, the relative ratio of decreasing temperature loss function, relative velocity of quenching parameter and the relative quenching velocity of loss function are all set as one; the magnification time of penalty is 1000; and both the penalty and objective function of failure solution are set as  $1.0 \times 10^{30}$ . The flow chart of optimization is as Fig. 4.

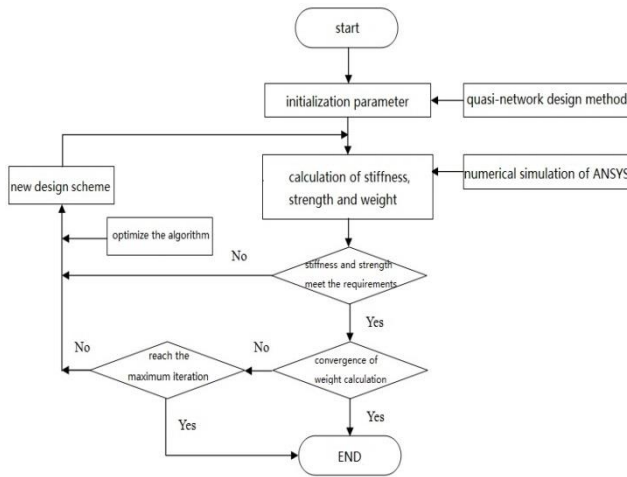


Fig. 4. Flow chart of first step optimization design of specially shaped tank of composite material - optimization design of mass

The optimization results from the calculation with parameters of Table 8 and the ASA algorithm are presented on Table 9. It shows that the ASA algorithm is very effective in the optimization of the weight of the tank that is decreased by 20.5%.

Table 9. The result of optimization design

Algorithm	Initial	ASA
ANG1	45	32
ANG2	45	24
R10	40	34
R1ANG1	72	72
R190	40	18
R20	20	8
R2ANG2	16	16
R290	8	8
R1STRAIN	0.005705	0.004269
R1STRESS (MPa)	716.82	563.43
R2STRAIN	0.001385	0.001796
R2STRESS (MPa)	173.84	225.37
RJSEQV (MPa)	185.77	269.93
MASS (kg)	329.52	261.97

4.2 Sub-step 2: maximizing the buckling limit

With the settled paving angles and the number of layers of each angle, the buckling limit of the laminated structure depends on the sequence of paving the layers [6]. The design of the laminated structure in this study is a balanced symmetrical laminated board. The optimization results of Table 9 indicate that the number of layers of RF1 part is relatively large, and it is inefficient to optimize the calculating time with the global optimization algorithm. Therefore it is more favorable and convenient to adopt the enumeration method to select the sequence, which can increase the efficiency of calculation [11].

The layer paving sequence can be determined primarily as the 8 ways of sequencing in Table 10 based on the results of ASA shown on Table 9 and by combining the general principles of layer design of composite material laminates.

Table 10. Layer sequence of the composite material of the tank

Number	Layer sequence of RF1	Layer sequence of RF2
Initial	$[0_{17}/\pm 32_{18}/90_9]_S$	$[0_4/\pm 24_4/90_4]_S$
1	$[\pm 32/0/[0/\pm 32/90/\pm 32/0]_8/90/\pm 32]_S$	$[0/\pm 24/90]_{4S}$
2	$[\pm 32/0/[0/\pm 32/90/\pm 32/0]_8/90/\pm 32]_S$	$[0_2/\pm 24_2/90_2]_{2S}$
3	$[\pm 32/0/[0/\pm 32/90/\pm 32/0]_8/90/\pm 32]_S$	$[\pm 24/0_2/\pm 24/90_2/\pm 24/0_2/\pm 24/90_2]_S$
4	$[\pm 32/0/[0/\pm 32/90/\pm 32/0]_8/90/\pm 32]_S$	$[ [\pm 24/90/\pm 24/0]_2/[90/0]_2 ]_S$
5	$[\pm 32/[0/\pm 32]_8/[0/\pm 32/90]_9]_S$	$[0/\pm 24/90]_{4S}$
6	$[\pm 32/[0/\pm 32]_8/[0/\pm 32/90]_9]_S$	$[0_2/\pm 24_2/90_2]_{2S}$
7	$[\pm 32/[0/\pm 32]_8/[0/\pm 32/90]_9]_S$	$[\pm 24/0_2/\pm 24/90_2/\pm 24/0_2/\pm 24/90_2]_S$
8	$[\pm 32/[0/\pm 32]_8/[0/\pm 32/90]_9]_S$	$[ [\pm 24/90/\pm 24/0]_2/[90/0]_2 ]_S$

Based on the eigenvalue (linear) buckling analysis in FEM, the clamped constraints of the bottom connection frame and the unit load (pressure) on the upper connection frame are conducted. Because the load imposed on the structure is the unit load in static stress analysis, the obtained coefficient of the buckling limit is the buckling limit of the structure. The buckling limit values of the 8 layer paving sequence are given in Table 11.

Table 11. The buckling limit values of different layer sequences

Number	Buckling limit (N)
Initial	$4.8610237 \times 10^6$
1	$5.8385854 \times 10^6$
2	$5.6821293 \times 10^6$
3	$5.7544069 \times 10^6$
4	$5.9606878 \times 10^6$
5	$5.8383219 \times 10^6$
6	$5.6819694 \times 10^6$
7	$5.7542284 \times 10^6$
8	$5.9603708 \times 10^6$

The statistics of Table 11 and Table 10 show that the layer sequence of RF1 has little effects on the overall buckling limit of the structure. In the Sequence 4, the buckling limit of structure is the largest, which is 1.23 times the lowest buckling limit. Therefore Sequence 4 is adopted as the design scheme of the laminates of the tank.

5. Conclusions and Remarks

We have proposed a structural optimization approach for the design of specifically shaped composite tanks in spacecrafts. Based on the application on a cone-shaped cylinder

body, the following conclusions can be made correspondingly.

1. The quasi-network design method combined with the finite element method can conduct the preliminary design the composite tank of complex loading condition. The preliminary design scheme can be adopted as the initial value of the optimization design.

2. The Adaptive Simulated Annealing (the ASA) can optimize the weight of the structure, decreasing the weight by approximately 20%.

3. When the number of layers is large, to maximize the buckling load of the structure, the enumeration method is used to select the sequence of layers, increasing the buckling load to 1.23 times of the previous tank. The method reaches a favorable result.

## Nomenclature

$E$	: Young's modulus
$\nu$	: Poisson's ratio
$G$	: Shear modulus

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