Research Article

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The enhancement of filament winding in marine launching rubber gasbag

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Abstract: The traditional craft of marine launching rubber gasbag that made by hand laying cord fabric has the disadvantages of irregular reinforcing direction and discontinuity of cord, which leads to the limitation of bearing capacity of gasbag and poor reliability. Based on the analysis of the structure of the rubber gasbag and geodesic winding pattern used in marine launching, the winding process design and experiment of the fiber reinforced rubber gasbag are carried out to solve the problem. The numerical simulation of the wound rubber gasbag is established by the finite element software ABAQUS in order to study the geometrical and contact nonlinearity of the gasbag, and the nonlinear relationship of parameters in application process, and then compare the application performance with those of the traditional cord fabric placement molding. Finally, the winding pattern test and deformation simulation experiment are carried out to verify the fact that the reinforced rubber gasbag with glass fiber / polyurethane composite material has a higher bearing capacity compared with the traditional handmade rubber gasbag. Thus, it provides theoretical and experimental evidence for the winding process of rubber gasbag.

Keywords: rubber gasbag; winding reinforcement; pattern design; polyurethane

1 Introduction

As the rubber gasbag has the advantages of low-cost, easy to use, reusability, etc, it is widely used in the field of safety

protection, transportation, construction, pipeline maintenance, marine launching and salvage etc [1]. The traditional fiber reinforced rubber process mainly consists of two ways: one is placing cord fabric covered with long continuous fibers, the other is mixing with short fibers in the rubber material. The rubber composite material which composes the marine gasbag is divided into three parts, rubber sealing layer, cord reinforced layer and external protective layer. The rubber sealing layer is used to seal the compressed air inside to maintain the pressure of the gasbag; The cord reinforced layer is mainly used to bear the internal pressure of the gasbag, the required type of cord material and the number of reinforcing layers depend on the compressive strength of the gasbag; The external protective layer made of anti-aging and abrasion-resistant material protects the interior structure from being damaged by external environment [2]. With the increasing of ships' size and tonnage, the carrying capacity of the gasbag required for launching is getting larger and larger, and the risk is getting higher and higher. In order to obtain the rubber gasbag with more enhanced strength of the cord fabric, a more expensive high-strength aramid fiber is used as reinforced cord. Simultaneously, the rubber used for the gasbag is natural non-polar rubber, which is easy to act on with the oil and the solvent, resulting in poor oil resistance and organic solvent resistance. The unsaturated double bonds that natural rubber molecule contains causes poor thermal, oxidation and ultraviolet resistance. In addition, the traditional fiber reinforced rubber gasbag molding mainly adopts placement process by manual or semi-automatic equipment in contour machining. The molding process is not only inefficiency, low precision, but also poor quality and low qualification rate of processed products, which is easy to cause immediate failure, resulting in economic loss and even endangering people's life in engineering applications. As a result, technological innovation or product optimization of rubber gasbags is urgently needed as the upgrading of technology and the increasing carrying capacity of gasbag in application. At present, European process and technology of rubber products are relatively developed. The TANIQ Company in Netherlands has rapidly developed and dedicated to research reinforced technolo-

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gies of rubber products [3], the Scorpo robots that can realize automatic winding and placing production process for different layers of rubber products. Rubicon in Germany has developed a cordless automotive hose production line that produces filament winding reinforced hose such as power steering hoses, fuel hoses, vacuum brake hoses, oil cooler hoses, tank hoses and coolant hoses.

Polyurethane with the characteristics of excellent wear resistance, good elasticity, oil resistance and solvent resistance, has been widely used in automobile, construction and machinery industries [4]. The application of inexpensively glass fiber polyurethane composite material and rubber material can improve wear resistance and corrosion resistance of products; reduce the consumption of rubber material; improve the comprehensive utilization value of rubber products. Simultaneously, because of compatibility of resin and rubber, resin can improve the product's performance as a reinforcing agent of rubber. Therefore, the paper presents a rubber gasbag that is enhanced the winding by glass fiber/polyurethane composite, based on the conclusion that the process integrity, cohesiveness and fiber strength efficiency of bundling untwisted aramid fiber and thermoplastic elastomers together into a bead, it is superior to the production mode of placing cord fabric. Based on a detailed analysis of the gasbag structure and the design of the winding process, a composite model of the rubber gasbag is established and the numerical calculation of gasbag compression simulation is carried out in order to analyze the relationship between the external load and the compression height. Finally, the gasbag wound experiment is carried out to provide the evidence for the design process of gasbag winding.

2 Materials and methods

2.1 Materials

Polyurethane elastomers which is formed by chemical reaction of thermosetting polyurethanes under the thermal, catalyst, pressure etc., has been widely used in automobile, mining, construction, printing and other industries, as it has the characteristic of not melting with heat, resolving by intense heat and excellent physical properties [5]. Glass fiber with high strength and low-cost has also been widely used in composite industry. The composite rubber material made of matrix rubber and reinforced fiber can not only maintain the flexibility, elasticity and abrasive resistance of rubber materials, but also enhance the anti-

Table 1: Material parameters of polyurethane rubber

Gel time (min)	Curing time (h)	Tensile Strength (MPa)	Elongation at break %	Density /(g/cm ³)
4-6	12	45	500	1.26

Figure 1: Gasbag winding experimental machine

compression and tensile strength of products and improve the anti-aging ability and service life of rubber gasbags.

The polyurethane elastomer material of Zibo Alex Hua Tian Rubber and Plastics Technology Co., Ltd. is used as the base material for rubber gasbag reinforcement, and the material performance parameters are shown in Table 1.

In this experiment, glass fiber is used as an augmented material for rubber gasbag winding, and the material performance parameters are shown in Table 2. The size of rubber gasbag used for winding experiment is as follows: diameter of poles 100mm, length of cone 1000mm, diameter of column 1000mm, length of column 1200mm.

2.2 Winding equipment

Gasbag winding experiment adapts composite material made of reinforced fiber and polyurethane matrix as the winding material, applying four-axis linkage method to complete the integral winding process of gasbag, through cone processing methods of combining the geodesic stable winding of variable winding angles with equal winding angle.

The overall mechanical structure of the gasbag winding machine mainly includes four parts: the spindle, the trolley, the outrigger structure and the guide wire tip. The spindle of the system is driven by 11KW motor of Yasukawa,

Table 2: Performance parameters of glass fiber

Elastic Modulus (MPa)	density (g/cm ³)	Elongation (%)	Poisson's ratio	Specific strength σ/ρ	Specific stiffness σ/ρ
7.3×10^4	2.54	4.8	0.22	13.8×10^4	2.9×10^6

and it rotates uniformly along the gasbag core mold. The trolley of system is driven by 4.4KW motor of Yasukawa, and it moves back and forth on the side of the gasbag core along the track with a certain speed; the outrigger structure of system is driven by 1.8KW motor of Yaskawa, and it is installed in the platform of trolley, when the trolley does reciprocating motion on both heads of the gasbag, the outrigger structure do concertina motion in the direction of the vertical carriage track; the guide wire tip of system is driven by 450W motor of Yaskawa, and it is installed in the outrigger structure, when the outrigger structure performs concertina motion, it does rotary motion along the telescopic direction of the outrigger structure. Gasbag winding machine experimental equipment is shown in Figure 1.

2.3 Geodesic path planning

This paper selects the spiral winding method as the gasbag winding process. As shown in Figure 2, the wiring of the gasbag is composed of a spiral section of the cone section and the column section. Spiral winding can provide both lateral and longitudinal strength in the overall structure design of the gasbag. The winding material is evenly distributed on the surface of the gasbag core mold with winding angle. As the carriage reciprocates along the track, the crossover phenomenon of the yarn occurs. Therefore, the winding rules of spiral winding can be analyzed by the number of intersections and the distribution of tangent points at the ends.

Figure 2: The sketch of helical winding

Filament winding path can be divided into geodesic winding and non-geodesic winding, the stable non-geodesic winding line of gasbag cone needs to meet the

equation

$$\cot \beta * Ln \frac{D}{d} = \pm \frac{K}{t} \int_{\alpha_1}^{\alpha_2} \varphi(\alpha) \cos \alpha d\alpha \quad (1)$$

In formula (1), D and d denote the large and small aperture of the cone section, α_1 and α_2 denote the winding angle of geodesic and non-geodesic pattern, β denotes half-apex angle of cone section, t denotes friction between winding material and core mold, α denotes winding angle, $\varphi(\alpha)$ denotes winding angle variation equation of non-geodesic pattern, and K denotes gear hopping indexing.

Because of the inflatable soft material of core mold and the tension in the fiber winding process, the deformation of the core mold will result in the decrease of the friction force t on the surface of the core mold so as to make the equation (1) inequitable. Furthermore, the condition of stable winding cannot be satisfied, and the phenomenon of slippage may occur, eventually affecting the quality of the winding product. Therefore, this design of the rubber gasbag adopts the way of geodesic winding.

Figure 3: The sketch of the head of gasbag

First of all, the geometric characteristics of the core mold are analyzed. Since the unstable winding area of the gasbag is mainly distributed on the side of the gasbag head, the winding of the conical segment will mainly be analyzed in the following aspects. The mathematical model of conical body of gasbag head is shown in Figure 3. The geometric shape of the conical head shows that the shape is formed by the rotation of the generatrix about the coordinate axis z , and the expressive formula of the conic

surface under polar coordinates is:

$$r(\theta, z) = \{r(z) \cos \theta, r(z) \sin \theta, z\} \quad (2)$$

In formula (2), r represents the radius of each point along z direction, θ is the center angle of the core mold and z is the z coordinate of the axisymmetric body.

The geodesic curvature of the cone can be obtained by Gauss curvature equation:

$$k_g = \frac{d\theta}{ds} = -\frac{d\alpha}{ds} - \frac{r' \sin \alpha}{r\sqrt{1+r'^2}} \quad (3)$$

According to differential geometry, Gauss theorem, geometric differential theorem and Euler formula we can see:

$$k_n = \frac{r''}{(1+r'^2)^{3/2}} \cos^2 \alpha - \frac{1}{r\sqrt{1+r'^2}} \sin^2 \alpha \quad (4)$$

In formula (4), k_n denotes normal curvature.

Set $k_g/k_n = \lambda$, and the differential equation of the trajectory can be obtained:

$$\begin{cases} \frac{d\alpha}{dz} = -\frac{r' \tan \alpha}{r} + \lambda b \\ b = -\frac{r''}{1+r'^2} \cos \alpha + \frac{\sin \alpha \tan \alpha}{r} \end{cases} \quad (5)$$

When λ is 0, the differential equation is the geodesic differential equation [6, 7].

2.4 Winding angle design

Realizing the geodesic winding of conical segment, it is necessary to mainly analyze and design the change rules of winding angle on conical segment. A schematic diagram's position of any doffing point in the conical segment is shown in Figure 4, and the geodesic unfolded drawing is shown in Figure 5.

The winding angle of the geodesic winding method has the following rules:

$$\frac{\sin \alpha_0}{\sin \alpha_i} = \frac{d_i}{d_0} \quad (6)$$

Where: d_0 represents the diameter of known point of the cone, d_i represents the diameter of any point i of the cone, α_0 represents the winding angle at the known point d_0 , α_i represents the winding angle of the geodesic at any point i . As the diameter of the pole directly affects the winding angle of geodesic trajectory, and small pole will cause the winding accumulation at the head and small winding angle of the cylinder body, which will reduce the circumferential mechanical properties of the cylinder body. Therefore, based on the existing experimental gasbag, this study sets

Figure 4: The sketch of the cone of the head of gasbag

Figure 5: The unfolding draw of geodesic line of the cone of gasbag

the diameter of the pole 200 mm to design the whole winding of the gasbag. According to the geodesic equation, the winding angle of the cone section of the cylindrical head with the diameter of 200-1000 mm can be obtained. The winding angle distribution of the cylindrical head cone section is compared with that of the geodesic planning with the poles of 100, 300 and 400 mm (as shown in Figure 6).

2.5 The center angle of rotation

According to the principles of gasbag segmentation analysis, the gasbag is divided into two segments, the column segment and the conical segment, analyzing the winding center angle. First of all, the analysis of the conical segment is shown in Figure 7. Since the conical segment adopts the variable winding angle processing method, the central angles at the unequal circular segment of the conical segment are inconsistent. The calculation method of the conical body winding center angle will be analyzed in the following aspects.

When the guide wire head completes a single-pass winding from the large port to the small port of the conical segment on core mode, the central angle of the core mold

Figure 6: Winding angles of geodesic trajectories with different poles

Figure 7: The sketch of cone of the head of gasbag

rotation is:

$$\gamma_1 = \frac{[\arcsin(\frac{D \times \sin \alpha_1}{d}) - \alpha_1]}{\sin[\arctan(\frac{D-d}{2 \times L_0})]} \quad (7)$$

In formula (7), we can see that the angle of the winding center is a fixed value in the winding process of cone section of the gasbag, and because the winding method of geodesic multi-tangent point is adopted, the path of winding fibers in the gasbag head is fixed, no matter where the winding fiber starts from any point of the gasbag tip. After the winding of the gasbag head is completed, the doffing point of the fiber winding should be the fixed position corresponding to the starting point of the winding. In the multi-tangential point machining process, the whole core mold is required to rotate corresponding angle during the round trip of the carriage. Therefore, the center of rotation

of the column segment is related to the number of tangent points.

If the number of cut points is n/K , it can be seen that the rotation center angle of the column segment should be:

$$\theta_{n-K} = \left(\frac{K}{n} + N \right) \times 360^\circ \pm \frac{\Delta\theta}{n} \quad (8)$$

In formula (8), K represents the jumping gear indexing of the tangent point, n represents the number of tangent point, and N represents integer multiple of cycle number of the barrel segment rotation.

2.6 Beyond length

During the gasbag winding process, since the yarn feed point at the guide wire head has a certain distance from the gasbag core mold, and the winding material has a certain width, the beyond length must be taken into consideration. The so-called beyond length is the position difference between the yarn feed point and the doffing point of the winding head along the direction of the axis of the core mold's rotation. The accuracy of the beyond length's calculation will directly affect the winding angle and the distribution of the tangential point of the pole hole on the side of the end caps. It even causes slip yarn on the end of the head, which affects the overall quality of the product.

Since the cross section of the gasbag along the direction perpendicular to the axis of rotation of the core mold is a circle, the calculation formula for the beyond length can be obtained from the geometrical analysis.

Figure 8: The sketch of the winding process

As shown in Figure 8, randomly take any moment in the winding process, then the radius of the circular section at this time is R , the distance between the yarn discharge point and the doffing point in the direction perpendicular to the axis of rotation of the core mold is ΔS_1 , and the winding angle is α , the yarn point is O , the doffing point is A , and the beyond length A_1A_2 at this point A can be

Table 3: Engineering Constants of Composite Materials

Engineering constants	E1 (MPa)	E2 (MPa)	E3 (MPa)	Nu12	Nu13	Nu23	G12 (MPa)	G13 (MPa)	G23 (MPa)
Value	1800	87	87	0.38	0.43	0.43	53	53	17.5

expressed:

$$\overline{A_1 A_2} = \frac{\sqrt{(R + \Delta S_1)^2 - R^2}}{\tan \alpha} = \frac{\sqrt{\Delta S_1 (\Delta S_1 + 2R)}}{\tan \alpha} \quad (9)$$

Since the winding material has a certain width, if the yarn width is assumed to be ΔS_2 , then the actual beyond length of the point should be:

$$L_{\text{beyond}} = \overline{A_1 A_2} + \Delta S = \frac{\sqrt{\Delta S_1 (\Delta S_1 + 2R)}}{\tan \alpha_i} + \Delta S_2 \quad (10)$$

In formula (10), L_{beyond} represents the beyond length at any point and α_i represents the winding angle at any point.

2.7 Modeling method

2.7.1 Nonlinear characteristic

Filament reinforced rubber gasbag is composite laminated structure with polyurethane as matrix material and reinforced fiber as reinforcing layer. It has the properties of elastic nonlinearity, viscoelasticity, heterogeneity and anisotropy [8]. This study only considers elastic nonlinearity but not viscoelasticity, so the gasbag has material nonlinearity. As polyurethane composites have the characteristics of high modulus, large deformation and rapid rebound of rubber, they produce large displacement and deformation when loaded. The gasbag has geometric nonlinearity. The contact relationship between the gasbag for launching is mainly related to the baseplate and the upper pressplate. The contact area of the gasbag varies nonlinearly with the radial deformation, which makes the elastic nonlinearity of the gasbag more obvious in the case of large deformation. The gasbag has contact nonlinearity.

2.7.2 Model Materials

Filament winding reinforced rubber gasbag is composite composed of fibers and resin matrix. In order to reduce the cost of simulation, the material properties of composite in ABAQUS are simulated by finite element method. In finite element analysis, the rubber layer of the gasbag is defined as an isotropic hyperelastic body, the composite layers are

Figure 9: The distribution of winding angles

defined as an elastic body and the material property defined as an anisotropic composite, the baseplate and the upper pressplate are defined as rigid bodies. At the same time, in the finite element simulation design, the thickness of composite layer is set to 10 mm, thickness of each layer is 1 mm, and the winding angles (fiber direction) of each layer are positively and negatively distributed. The material and parameters (as shown in Table 3) of composite winding layer are tested and provided by Hengshui Rubber Technology Co., Ltd. The conical composite layers are evenly divided into 20 assemblies along the axis of the gasbag, and the edge winding angle is given to each of the assemblies, that is, the distribution of winding angle varies with the diameter, as shown in the Figure 9.

2.7.3 Loading

As a kind of thin-walled composite, rubber gasbag will exhibit displacement and deformation similar to rubber material under the action of force, which is beyond the scope of linear theory and has highly geometric nonlinearity [9]. This geometric nonlinearity is caused by the large deformation of the gasbag at work. Its structural stiffness depends not only on the material and initial deformation, but also largely on the stress distribution and displacement

after loading. In order to simulate the boundary displacement and force of the gasbag, the initial internal pressure is firstly applied to simulate the inflatability of the gasbag, and then the gasbag that has applied the initial internal pressure is closed, and the vertical displacement of the rigid body with time is applied to simulate the loading process.

2.7.4 Contact Relation

The contact that occurs after the gasbag is deformed by force cannot be accurately determined in advance, that is, the boundary condition is not given before the calculation in the contact problem, but is the result of the calculation. In the process of contact, the area and pressure distribution of contact surface change with the external load. Therefore, surface to surface contact is used to establish the relationship of the freedom and deformation between joints of the baseplate and the outer surface of the gasbag, and the binding relationship between the composite and the rubber layer.

2.7.5 Boundary Conditions

Fixed boundary conditions are applied to the baseplate, and then all degrees of freedom are fixed except the vertical direction. The boundary of a given cavity is a set of cell-based surfaces, the normal direction of the surface points to the inside of the cavity, the initial pressure field is 0.05 MPa and the initial temperature field is 300 K. The components and boundary conditions of the model are shown in Figure 10.

Figure 10: Components and boundary conditions

2.7.6 Air Simulation

The main difficulty of gasbag modeling is the coupling between structural deformation and the pressure exerted by the contained fluid on the structure. The mechanical response of the structure depends not only on the external load but also on the pressure of the contained fluid inside, simultaneously, the pressure of the internal gas is also affected by the structural deformation. The gasbag is subject to both atmospheric pressure and internal gas pressure. The pressure of internal gas plays a decisive role in the rigidity of the gasbag. ABAQUS can use surface-based fluid modeling methods to simulate aeration that provides interaction between structural deformation and internal pressure through the surface, and it performs better than static fluid modeling methods. The surface-based fluid cavity model has the ability to analyze such coupling problems by assuming that the internal fluid cavity is completely filled with fluid and it has consistent properties and states [10, 11]. Therefore, in this paper, ABAQUS is used to define the fluid cavity model and the initial internal pressure of the gas at 0.05MPa and the initial temperature of 30°C. The aerodynamic model is used to simulate the effect of the internal gas on the stiffness of the gasbag.

3 Results and discussion

3.1 Dry yarn fiber winding experiment

Firstly, based on the design of the above process parameters, the experiment of geodesic winding with dry yarn fiber is carried out to verify the feasibility of the winding process, determine the winding angle and the winding path by four-axis winding machine.

The movement of each axis is stable during the winding process of the rubber gasbag based on the four-axis winding machine. The winding pattern is as shown in Figure 11 and the measured data are as follows: the distance between adjacent gauges is 50.4mm, and the width of yarn is 50mm in this experiment, then, the precision of the winding path is 0.4mm. Therefore, the rubber gasbag winding machine can reach the high-precision winding (repeated positioning accuracy) of rubber gasbag.

In order to verify the stability of the winding pattern (the geodesic winding method of changing wound angle can meet the stable winding of the rubber gasbag or not), the shape of the gasbag can be partially changed by hand after molding to observe whether the winding pattern is stable or not, the effect is shown in Figure 12. The linear

(a) The linear of one layer winding

(b) The linear of cone

Figure 11: Results of winding linear

stability experiment verifies that the designed rubber gasbag winding process can realize the stable winding of the rubber gasbag.

3.2 Simulation results

The rigid body is used to load and unload the gasbag. The circumferential stress of the wound composite reinforced gasbag after loading is shown in Figure 13. The maximum value (64.96 MPa) is mainly distributed at the two cone ends; the longitudinal stress is shown in Figure 14. The maximum value (2.68 MPa) is mainly distributed at both ends of the cone section and in the middle of the column section.

The overall stress distribution is shown in Figure 15, and the maximum Mises stress (65.9 MPa) in the composite material layer is mainly distributed in the middle of the cone and in the periphery of the contact between the gasbag and the rigid body. This stress concentration is mainly

(a) The stability experiment of the cone linear

(b) The stability experiment of the cylinder linear

Figure 12: Stability experiment of winding linear

Figure 13: Distribution of circumferential stress

because the fact that the gasbag used in this experiment is not the standard size of ship launching gasbag, and the composite material layer adapts method of the equal thick-

Figure 14: Distribution of longitudinal stress

Figure 15: Distribution of overall stress

ness modeling, however, the actual taper winding layer is thicker near both ends. As a result, there is a certain amount of error in the simulation results.

3.3 Discussion

The comparison of the relationship between compression and internal pressure of fiber wound reinforced rubber gasbag and the conventional cord cloth laying rubber gasbag is shown in Figure 16. In the case of the same compression, the maximum value of the internal pressure of the fiber wound reinforced rubber gasbag is improved by about 20% compared with that of the cord cloth laying rubber gasbag, that is, its internal pressure bearing capacity is increased by nearly 20%. The comparison of relationship between the compression and the external load of the conventional rubber gasbag laid with the cord cloth is shown in Figure 17. In the case of the same compression, the external load required to compress the rubber gasbag is increased by approximately 30%, means that its bearing capacity is

Figure 16: The relationship between compression and internal pressure

Figure 17: The relationship between amount of compression and external load

increased by 30%, comparing to the rubber gasbag placed by cord cloth.

4 Conclusions

Based on the limitations of the increasing size of the ship and the bearing capacity of the cord rubber bladder, the composite material system of glass fiber/polyurethane and the theory and process of filament winding are used to design the composite winding reinforced rubber gasbag, which greatly increases the carrying capacity and production efficiency of the rubber gasbag. The non-linear finite element analysis method is used to obtain the non-linear mechanical characteristics of such a launching gasbag. The experiment of dry fiber yarn winding pattern and

deformation simulation of gasbag are carried out, which shows that it is feasible to use the glass fiber/polyurethane composite material instead of the traditional laying cord fabric. The calculation results can be used to provide basis for the design of gasbag winding process.

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