Design, Analysis, Fabrication, and Test for Low-Cost and Out-of-Autoclave Composite Airship Gondolas

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Abstract: Out-of-autoclave (OoA) processing has the advantages of low cost, light weight and environmental protection, and has become a hot spot in the field of composite materials worldwide. This paper investigates the application of OoA processing in the gondola of the AS700 civil manned airship. The production cost of gondolas is reduced by selecting low cost materials such as glass fiber, PVC foam and OoA processing. The porosity of parts is reduced and controlled at about 2% by optimizing the edge breathing of prepreg during curing. The maximum tensile strain of the glass fiber is 4 593 με; its maximum compressive strain is 3 680 με; and its maximum shear strain is 4 884 με. The maximum Von Mises stress of the foam is 0.70 MPa. These settings all meet the margin requirement of safety. Finally, the ultimate load test of the gondola is carried out to verify the safety of the gondola structure. Our study presents critical parameters for the gondola design, including load, structure, strength, and manufacturing process test, and provides certain references for the design of similar products.

Key words: out-of-autoclave (OoA) processing; airship gondola; foam sandwich; porosity control

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0 Introduction

With the development of composite technology, composite materials have been increasingly applied to aviation structures[1-4]. Autoclave forming process has been widely used in aerospace structural parts because it can produce low porosity parts by applying high pressures and well-defined thermal curing cycles[5]. Vacuum bag-only (VBO) is an out-of-autoclave (OoA) processing, which has advantages in low cost and parts limitation, and has attracted the interest of aerospace industry recently[6-7]. However, the low applied pressure of 1×10^5 Pa in VBO prepreg processing[8] leads to parts with a relatively low fiber volume fraction and more defects in the form of voids[9].

The ratio of the void volume to the material volume, commonly known as the void volume ratio or the void volume fraction, is a key parameter to characterize the quality of parts[10]. Mechanical properties such as the interlaminar shear strength, material toughness and moisture uptake are greatly affected by the void content[11]. The increase of porosity will lead to significant deterioration of mechanical properties of parts[12-13]. Generally, the porosity of aerospace structural parts needs to be controlled below 2%[11].

Main drivers of the porosity formation are the length of the part or its distance from the vacuum source[14], the quality of vacuum available during processing[15], material characteristics such as the percentage of initial impregnation of the tow[16-18], textile architecture and air permeability[19-20], as well as resin characteristics[21-22]. Other factors

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such as high moisture uptake[10], prepreg out time[23], as well as local defects[24], can also influence the final porosity content of a part produced by OoA.

Naresh et al.[25] suggested that thermo-mechanical compaction of prepregs was one of the key stages in VBO manufacturing process, and the compaction stage and the first dwell period in a cure cycle were the most critical steps, during which the elimination of voids was possible. Serrano et al.[11] investigated the influence of the pre-cure compaction time and cure cycle on the porosity level, and demonstrated that the pre-cure compaction played an important role in the manufacturing of "void-free" laminates. Grunenfelder et al.[26] emphasized the need for adequate edge-breathing in VBO cure. Yuan et al.[27] found that increasing temperature platform properly was conducive to the air out before the resin gelated and the decrease of porosity of parts. Kim et al.[28] pointed out that the production of high-quality parts using OoA prepreg required out-time and humidity control and/or appropriate thermal control to ensure adequate flow time and to fully impregnate the prepreg during processing. Some researchers[29-30] carried out experimental studies on the influence of ambient relative humidity, vacuum level, room temperature hold time, and part length on porosity. Increased relative humidity and reduced vacuum levels both increased void contents. For the same vacuum hold times, a longer flow distance for air evacuation increased porosity and created a porosity gradient along the evacuation direction. Porosity was fully eliminated in the case of exposure to 0% relative humidity and a long (24 h) vacuum hold.

The new generation of OoA prepreg can produce parts[24,31-34] with the same quality as the autoclave through VBO processing, such as sandwich panels parts[33], skin panel[35], space launch vehicle fairing[36], aircraft cabin frame[37], aft cooling duct[38], the fuselage of advanced composite cargo aircraft[39], etc.

Gondolas are the important part of airships, but little relevant literature has focused on them. Based on the AS700 civil manned airship, the engineering application of low-cost composites and OoA processing in the airship gondola is carried out in this paper. First, the gondola design and the finite element model analysis results are introduced. Next, the fabrication of the gondola is described. And then the test results are analyzed. Finally, the material selection and process selection for low-cost design are recommended.

1 Design

1.1 Layout

AS700 civil manned airships can be used in tourism, aerogeophysical prospecting, aerial survey, aerial photography, emergency rescue, etc. For tourism, the gondola is located in the lower abdomen of the airship and carries two pilots and eight passengers, or one pilot and nine passengers.

According to its function, the gondola can be divided into the cockpit, the passenger compartment and the fuel compartment, as shown in Fig.1. Components in the cockpit include the driver's seats, a dashboard, the center console, the side console, the top control panel, the front windshield, etc., and the ballast system is arranged at the bottom. The passenger compartment includes passenger seats, doors and the sightseeing glass. Steel cables and wire harness channels are installed below the floor. The landing gear is arranged at the rear of the bottom. The fuel tank is arranged in the fuel compartment, and the engine and the steering system are installed on the side. The gondola is about 7.2 m long, 1.9 m wide and 2 m high. When the fuel tank is full, the total mass on the gondola is

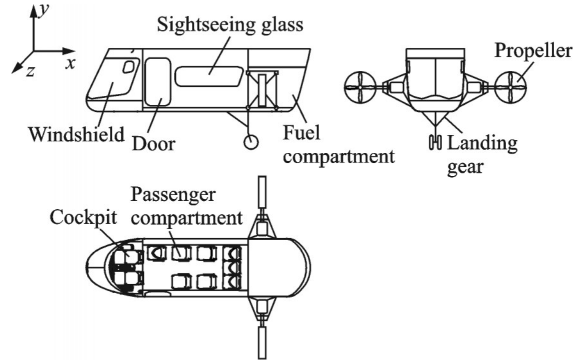

Fig.1 Layout of the gondola

about 3 000 kg. The gondola design should meet the requirements of aesthetics and low cost except for the conventional design requirements and airworthiness provisions.

1.2 Structural design

According to the general layout and load distribution of the gondola, the gondola framework structure is arranged. The gondola framework is composed of the frame (common frame and reinforcing frame), the top ring beam, the window frame, the door frame and the floor beam. The reinforcing frame adopts metal structure to bear concentrated load, and the other structures adopt foam sandwich composite structure to reduce structural weight and obtain structural stiffness. In order to facilitate molding and reduce the deformation of parts, the foam sandwich structure uses symmetrical ply[40] as far as possible. The door frame and the window frame are integrated with the skin, and the sandwich structure of skin is smoothly transferred to the laminate structure of door frame and window frame. The two-component epoxy resin adhesive is used for cementation between the composite parts. The theoretical cementation gap is 1 mm and cementation is carried out at room temperature. The theoretical mass of the gondola is 340 kg.

2 Model Results and Analysis

According to the airworthiness provisions, there are nearly 30 load conditions for the gondola. They are divided into three groups: Structural mass inertia force (including overload coefficient), landing gear load and propeller load. The overload coefficient includes flight maneuver overload, gust load overload and emergency landing overload. This paper does not discuss the emergency landing conditions, but introduces three severe conditions: The combination of the maximum continuous power of the engine and the designed maneuvering conditions (load condition No.1), the landing gear horizontal landing (load condition No.2), and the landing gear sideslip landing (load condition No.3). The loads of each condition are shown in Tables 1—3. The coordinate system is shown in Fig.1,

Table 1 Load on the gondola in load condition No.1

Load condition	F_d/N	Load in the plane of propeller (Unilateral)			
		F_x/N	F_y/N	F_z/N	M_{x_1}/(N·m)
1	50 078	−4 750	0	0	−1 112

Table 2 Load on the gondola in load condition No.2

Load condition	G_t/N	Landing gear load/N		
		x	y	z
2	32 732	20 370	25 463	0

Table 3 Load on the gondola in load condition No.3

Load condition	G_t/N	Landing gear load/N		
		x	y	z
3	32 732	0	41 932	23 063

the x-axis is along the longitudinal direction of the gondola, the y-axis along the vertical direction of the gondola, and the z-axis is along the lateral direction of the gondola. The total gravity G_t includes the gravity of the gondola (3 332 N) and the gravity of the cargo carried on the gondola (29 400 N). In Table 1, the dynamic overload coefficient f_d is 1.53, mass inertia force on the gondola $F_d = G_t f_d$, M_{x_1} refers to the torque in the propeller plane, and x_1 refers to the local shafting parallel to the x-axis with the propeller loading point as the origin. The allowable value of the composite and foam design σ_a is measured by the test. According to the airworthiness clause, the safety factor of the composite material f_s is 1.5, and the environmental factor of the composite material f_e is 1.25 besides the safety factor. The shell element is used in the laminate structure and the foam. In model analysis, the primary performance metric is margin of safety υ, which is computed as

$$\upsilon = \frac{\sigma_a}{\sigma_m f_s f_e} - 1 \tag{1}$$

where σ_m is the maximum calculated stress.

The calculation results of load condition No.1 are shown in Table 4, and the cloud diagram of the glass fiber tensile strain is shown in Fig.2. The maximum stress of the composite panel appears near the top skin of the frame, and the minimum margin of safety is 1.54. The maximum stress of foam appears

Table 4 Calculation results of load condition No.1

Parameter	Maximum	Margin of safety
Tensile strain of glass fiber/με	1 825	1.54
Compression strain of glass fiber/με	1 088	2.53
Shear strain of glass fiber/με	1 476	2.52
Von mises stress of foam/MPa	0.11	5.91
Shear stress of foam/MPa	0.06	10.33
Overall displacement/mm	7.55	

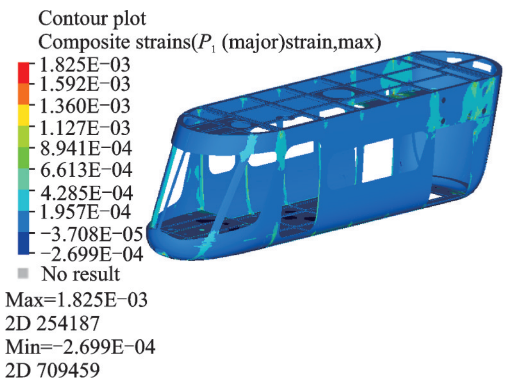

Fig.2 Cloud diagram of the glass fiber tensile strain under load condition No.1

on the boundary of frame web, and the minimum margin of safety is 5.91. Overall, the glass fiber and foam have greater residual strength under this condition.

The calculation results of load condition No.2 are shown in Table 5, and the cloud diagram of the glass fiber tensile strain is shown in Fig.3. The calculation results of condition No.3 are shown in Table 6, and the cloud diagram of the glass fiber tensile strain is shown in Fig. 4. For load conditions No.2 and No.3, the maximum stress of composite panel both appears in the skin near the landing gear joint, and the minimum margin of safety for load condition No.2 is 0.01, while the minimum margin of safety for load condition No.3 is 0.04. The maximum stress of the foam both appears on the skin

Table 5 Calculation results of load condition No.2

Parameter	Maximum	Margin of safety
Tensile strain of glass fiber/με	4 593	0.01
Compression strain of glass fiber/με	2 914	0.32
Shear strain of glass fiber/με	3 513	0.48
Von mises stress of foam/MPa	0.70	0.09
Shear stress of foam/MPa	0.40	0.70
Overall displacement/mm	10.93	

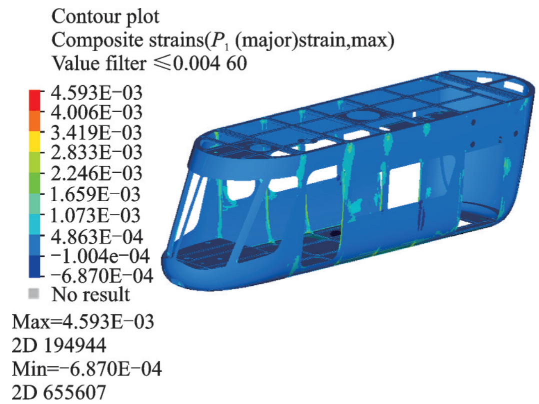

Fig.3 Cloud diagram of the glass fiber tensile strain under load condition No.2

Table 6 Calculation results of load condition No.3

Parameter	Maximum	Margin of safety
Tensile strain of glass fiber/με	3 967	0.17
Compression strain of glass fiber/με	3 680	0.04
Shear strain of glass fiber/με	4 884	0.06
Von mises stress of foam/MPa	0.46	0.65
Shear stress of foam/MPa	0.27	1.52
Overall displacement/mm	7.39	

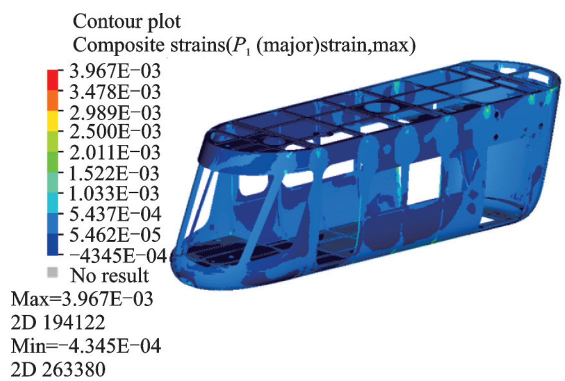

Fig.4 Cloud diagram of the glass fiber tensile strain under load condition No.3

boundary near the landing gear diagonal strut joint, and the minimum margin of safety for load condition No.2 is 0.09, while the minimum margin of safety for load condition No.3 is 0.65. Compared with those of load condition No.2, the area of structure with higher stress and shear stress in load condition No.3 is larger. Under the two conditions, the margin of safety for the glass fiber and the foam are both small. Since the load calculation is conservative, the local element mesh is large. The structural safety will be verified through the limit load test.

3 Fabrication

3.1 Manufacturing of composite parts

In order to reduce the void content, the impregnation rate of prepreg resin is improved by optimizing the curing temperature curve to reduce the flow-induced void content. By optimizing the VBO layup of parts, the air entrapment in the curing process, and the gas-induced void content are reduced. Using small samples to analyze the void content of different processes, the curing temperature curve of parts is obtained, as shown in Fig.5. By adding dry fiberglass strands at the edge of the layer to improve the edge breathing of prepreg, the void content of parts can be effectively reduced and the quality of parts can be improved. The VBO layup of parts is shown in Fig.6.

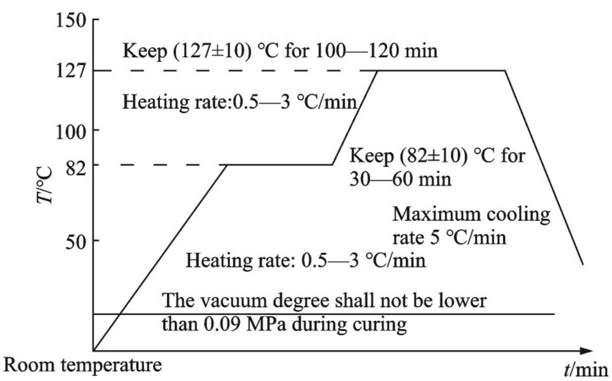

Fig.5 Curing curve of prepreg

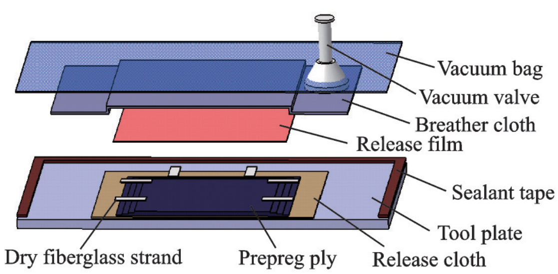

Fig.6 VBO layup schematic

In addition to optimizing the edge breathing of prepreg during curing, the following aspects should be paid attention to:

(1) When the prepreg is taken out from the cold storage, the packaging bag cannot be opened. It needs to be placed at room temperature for several hours until the prepreg is heated to room temperature.

(2) It is necessary to vacuum in the process of laying when there are many layers.

(3) As shown in Fig.7, the stepped edge with dry fiberglass strands can make the air flow between the layers faster.

(4) Multiple vacuum valves need to be arranged for parts with large area.

(5) The thickness of the tool plate need to be uniform to ensure that the temperatures rise of different parts of prepreg plies rise uniformly.

(6) The air tightness of the mold is tested. The vacuum should be more than 9.2×10^4 Pa and the pressure drop should not exceed 2×10^3 Pa in 5 min.

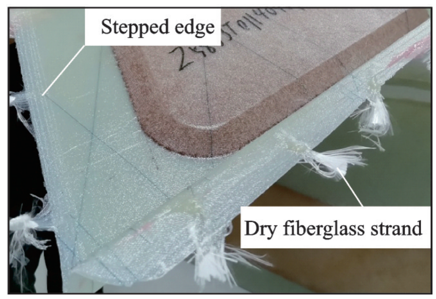

Fig.7 Stepped edge with dry fiberglass strands

Through the above measures, the void content of the parts can be effectively reduced to about 2% by micro-photograph image analysis. The void content of aerospace structures is acceptable at levels below 2%[11]. Fig.8 shows the tool with lay-up and vacuum bag

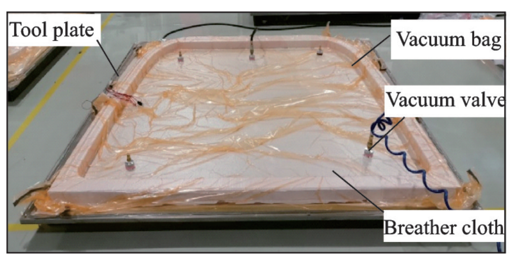

Fig.8 Tool with lay-up and vacuum bag

3.2 Assembly

The gondola is assembled by assembly frame, and the assembly sequence is from bottom to top, from inside to outside. The order is the bottom skin, the frame, the floor beam, the floor, the side skin and the top plate. Most parts are located by face and pin holes on the assembly frame. After positioning, the parts are assembled by cementation or screw connection. When the cementation gap is greater than the design value, the composite gasket is added to reduce the gap. Each skin and frame is arranged with four pin holes for positioning, and three pin holes can be inserted smoothly during assembly, which shows that the manufacturing accuracy of parts is high.

4 Test

4.1 Test process

In order to verify the safety of gondola structure and the rationality of strength calculation method, the above three severe conditions were tested, and the test loads were set as the loads in Tables 1—3 multiplied by the safety factor of 1.5. Fig.9 shows the gondola test.

Fig.9 Actual gondola within the test fixture

The gondola was fixed and restrained with the longitudinal steel beam through the top joint. The landing gear load and the propeller load were loaded by the hydraulic actuator, and other loads were loaded by the counterweight. Several strain gauges were arranged on the outside of the gondola skin, the frame and the beam to monitor the stress of the structure. The test data were collected and stored in real time through the data acquisition box, and the actuator was loaded by the coordinated loading system. Data acquisition and actuator loading were carried out by the operator in the control room.

For each load condition, the pre-test of 40% limit load was carried out to eliminate the test gap. debug The test equipment was debugged, and unloaded to 0 after loading. Then, the structure was loaded step by step to 67% ultimate load for 30 s to observe whether there was harmful deformation. Then, the structure was loaded step by step to 100% ultimate load for 3 s to observe whether the structure was damaged and then unloaded to 0.

4.2 Test results and analysis

Three test conditions were loaded successfully, and no harmful deformation and damage were found, which indicated the safety of the gondola structure. The tensile, compressive and shear strain values of the composite measured by the strain gauge under load condition No.2 were compared with the predicted values of the finite element model, as shown in Figs.10—12.The error statistics are shown in Table 7. Although the predicted compression strain values of the three strain gauges differ greatly from the test values, the other errors are less than 30%. The poor correlation of some data is due to the position error of the strain gauge, the strain gauge in the high strain gradient region, the stiffness error of the finite element model and stati-

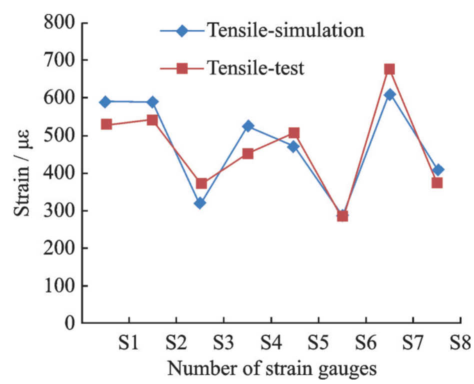

Fig.10 Comparison of tensile strain under load condition No.2

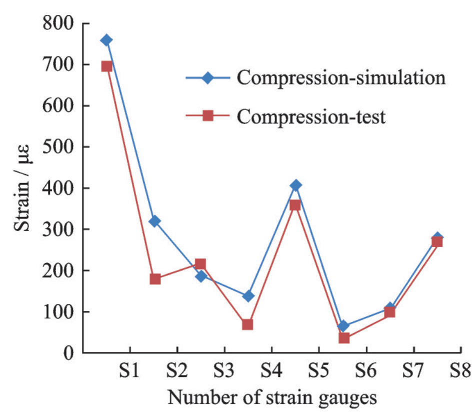

Fig.11 Comparison of compression strain under load condition No.2

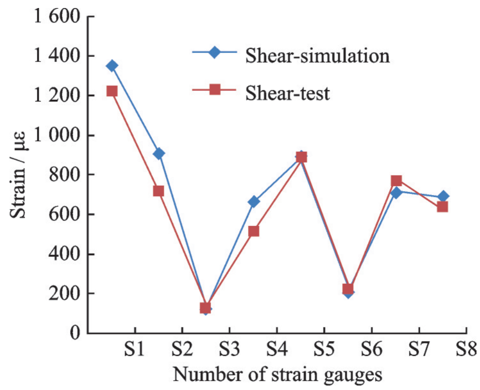

Fig.12 Comparison of shear strain under load condition No.2

Table 7 Error between simulation value and test value

Strain gauge number	Error/%		
	Tensile strain	Compression strain	Shear strain
S1	11	8	10
S2	8	82	27
S3	13	15	10
S4	16	124	29
S5	7	12	1
S6	4	87	7
S7	9	14	6
S8	11	4	9

cally indeterminate constraints.

5 Cost Analysis

The gondola design always implements the requirements of low-cost design, and comprehensively considers the aspects of material selection, process, weight, mechanical properties and porosity.

(1) In the manufacturing process of composite parts, raw materials and labor account for a large majority of costs, with contributions from equipment, tooling, energy and consumables being comparatively small[41]. Compared with carbon fiber prepreg and PMI foam, the cost of gondola materials for glass fiber prepreg and PVC foam can be reduced by about 50%. The quality inspection of glass fiber parts can be used visually, while the qualiy inspection of carbon fiber parts requires ultrasonic testing and porosity test plates. Although the resin infusion process using dry fiber and pure resin is better than VBO prepreg curing for economy and environment, the weight is unacceptable.So it is not used.

(2) The selection of VBO prepreg curing rather than autoclave curing is based on the following considerations. First, the cost of autoclave curing in equipment, mold and energy is higher than that of VBO prepreg curing[41]. At the same time, due to the large length and size of the gondola skin, it is easier for VBO oven curing to form parts as a whole, thas the assembly frame is simplified and the expensive and time-consuming assembly is reduced[42]. As the gondola parts are made of foam sandwich structure, the VBO prepreg adopts low pressure technology, and the defective rate can be reduced by reducing the defects caused by autoclave, such as honeycomb core crushing and panel depression. Compared with autoclave curing process, VBO prepreg process has the same weight, slightly poor mechanical properties and porosity, but acceptable.

(3) VBO prepreg cure improves the autoclave cuing in several environmental performance metrics (greenhouse gas emissions, resource use, ecosystem quality and human health) by between 10% and 20% (as measured using each category's appropriate unit), primarily through reductions in energy consumption[41]. With the development trend of energy conservation, emission reduction and green aircraft, the research and application of VBO prepreg forming process is the direction of development in the future.

6 Conclusions

The AS700 civil manned airship gondola is designed and fabricated using low-cost composites and OoA processing. The cost of product development and batch production can be effectively reduced by selecting glass fiber prepreg, PVC foam and OoA processing. The composite parts are manufactured by the layer method, and they are only compacted and cured in the oven under vacuum pressure. The porosity of the parts can be reduced to about 2% by optimizing the edge breathing of the prepreg during the curing process, which meets the requirement of engineering application. During the assembly process, the positioning hole of the part fits well with the positioning pin of the mold frame, indicating that the part has high precision.

Three severe load conditions are selected to carry out the limit load test. The test shows that the gondola structure has no harmful deformation under 67% limit load and no damage under 100% limit load, which verifies the safety of the structure.

Considering the impact load of the landing gear, the reinforcing frame connected with the landing gear adopts metal materials. The metal frame and the composite skin adopt cementation and bolt connection, which brings about structural weight gain and cost increase. Further research is needed to ensure that the reinforcing frame adopt composite materials can meet the requirements of the whole life cycle.

This paper introduces the load, structure, strength, manufacturing process and test of the manned airship gondola, and demonstrates that it is feasible to choose low cost materials such as glass fiber and PVC foam, and use OoA processing to produce manned airship gondolas. The research results of this paper are consistent with the development prospect of low cost and green production of aircraft, and can provide certain references for the design of similar products.

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低成本非热压罐复合材料飞艇吊舱设计、分析、制造和试验

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摘要：非热压罐成型(Out-of-autoclave processing，OoA)具有成本低、质量轻和绿色环保等优点，已成为世界复合材料研究领域的热点。本文介绍了OoA成型工艺在载人飞艇AS700吊舱上的应用。通过选择低成本材料(如玻璃纤维、PVC泡沫)和OoA成型工艺降低了吊舱的生产成本，通过优化固化过程中预浸料的边缘呼吸降低了零件孔隙率，使吊舱零件孔隙率控制在2%左右。吊舱结构中玻璃纤维的最大拉伸应变为4 593 με，最大压缩应变为3 680 με，最大剪切应变为4 884 με，泡沫最大Von Mises应力为0.70 MPa，满足安全裕度要求。同时，开展了吊舱极限载荷试验，验证了吊舱结构的安全性。本文对载人飞艇吊舱载荷、结构、强度、制造工艺和试验等做了介绍，可为同类产品设计提供一定的借鉴。

关键词：非热压罐成型；载人飞艇吊舱；泡沫夹心结构；孔隙率控制