DEVELOPMENT OF LIGHTWEIGHT CORRUGATED CYLINDER FOR SATELLITE PRIMARY STRUCTURE

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ABSTRACT

Composite has been widely used in the aerospace industry for its excellent specific stiffness and strength properties. Therefore a novel high modulus carbon fiber BHM3 and supporting cyanate ester resin BS4 were developed for forming an ultra-thin unidirectional prepreg. Based on this composite system BHM3/BS4, the corrugated shell cylinder which is the primary structure of a typical communication satellite platform, was developed. In order to reduce the weight of this corrugated shell cylinder, multi-objective optimization software ESSOS was used with Patran/Nastran to give the minimum layup number of different area. About 5% structural weight reduction was achieved and the layup scheme was simplified for easier manufacture. To verify the effectiveness of the aforementioned optimization and manufacturing crafts, typical subcomponent structures were manufactured and tested firstly to reduce the risk of directly development of the full-size cylinder according to the "building block" testing approach. The test result indicated that the design and manufacturing crafts are suitable to be extended to the full-size product. The full-size corrugated shell cylinder was then manufactured using prepreg by hand layup, and cured using autoclave, the mass of product is about 27kg. The cylinder was qualified by using simultaneously loading equipment with the maximum vertical and lateral load. All strain and deflection data showed linear behavior and no detrimental damage and deformation was found. Furthermore, this full-size cylinder was then mounted with analog counterweight and then perform sine-vibration test. Based on the static and dynamic test data, it was concluded that this corrugated shell cylinder met various technical requirements successfully and can be used as a lightweight primary structure of satellite.

1 INTRODUCTION

Composite materials are of widespread use in the field of aeronautics and astronautics due to the excellent specific stiffness and strength properties. Especially, the carbon fibers with high modulus are indispensable materials for the spacecraft primary structures. So far, domestic carbon fibers BHM3, the properties of which are equal to M40, have been developed. The corresponding cyanate ester resin system has been developed as well. Thus the composite materials system BHM3/BS4 with excellent mechanical properties has been formed, and it meets the requirements of space environment and can be applied to various light-weight structures of spacecraft.

The central cylinder, located at the center of the satellite, is usually used as the primary structure for the communication satellite[1]. The propellant tank is arranged in the cylinder. Outside the cylinder are the box-shaped structures made of honeycomb panels, which are used for placing various instruments and other large parts, such as solar arrays and antennas. The central cylinder should meet the requirements of strength, stiffness, interface and precision requirements. The primary cylinder forms include honeycomb sandwich shell, skin stringer and grid cylinder, of which the corrugated shell is a thin-wall light-weight shell structure and it can be used as strengthening structures by making composite materials into concavo convex corrugation structures along the axial direction.

In this paper, the mechanical properties of the domestic high-modulus composite materials system are discussed, and then application research on the primary structure is conducted to verify this kind of composite can be used for satellites.

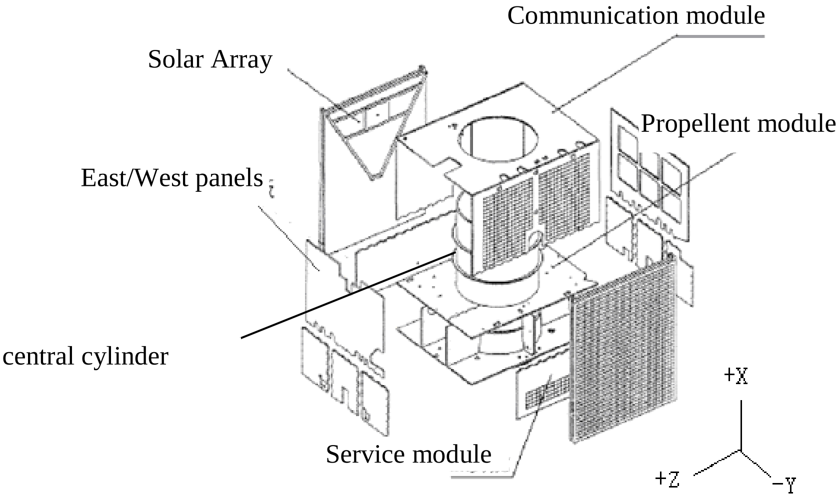

Figure 1: Typical structure of communication satellite.

2 MECHANICAL PROPERTIES OF COMPOSITES

2.1 Fiber filament

The comparisons of mechanical properties between domestic high-modulus carbon fibers BHM3[2] and Toray M40 are listed in Table 1. As it can be seen, the mechanical properties of BHM3 are superior to M40-3k fibers and they are of similar density. Compared with M40J fibers, the fibers BHM3 are of relative lower tensile strength, lower fracture elongation and higher linear density.

Materials	Tensile Strength	Tensile Modulus	Elongation	Linear Density	Density
	[MPa]	[GPa]	%	g/km	g/cm^3
BHM3-3k	3100	410	1.0	181	1.81
M40-3k	2740	392	0.7	182	1.81
M40J-3k	4410	377	1.2	113	1.77

Table 1: Mechanical Properties of fiber.

2.2 Thin prepreg

The monolayer thickness of the prepreg used on the satellite of our country is 0.1mm~0.125mm. Thinner prepreg thickness can reduce the weight of the structure, increase the design flexibility. Corresponding thin prepregs (0.08mm and 0.06mm) have been developed based on BHM3/BS4. For honeycomb panel of [0/+45/-45/90/C] plies, the mass reduces 0.3kg/m^2 when using the skin made of 0.08mm thickness prepreg compared with the skin made of 0.1mm thickness prepreg.

2.3 Fiber Composites

The mechanical properties of composite system BHM3/BS4 are listed in Table 2[3]. High performance modified cyanate ester resin is of high fracture elongation and it can give full play to the performance of fiber reinforcement, meanwhile, the interfacial bonding strength is relative high between them. As a result, the laminate is of good longitudinal tensile strength and interfacial shear strength. Besides, cyanate ester resin is of good dimensional stability, low dilution rate and good toughness, so the cyanate matrix composites are preferred for the satellite structures.

Material		BHM3/BS4
0ºTensile Strength	[MPa]	1567
0ºTensile Modulus	[GPa]	244
0ºCompression Strength	[MPa]	915
0º0ºCompression Modulus	[GPa]	207.9
90ºTensile Strength	[MPa]	33.8
90ºTensile Modulus	[GPa]	7.42
90ºCompression Strength	[MPa]	60
90º0ºCompression Modulus	[GPa]	8.02

Table 2: Mechanical Properties of Composite.

3 DESIGN AND OPTIMIZATION OF CORRUGATED CYLINDER

3.1 Original design state

The diameter and the height of the central cylinder are about 1100mm and 2200mm respectively. The structure is connected by a carbon corrugated cylinder and an aluminum alloy adapter. The height of the corrugated cylinder is about 2000mm and the design capacity is no more than 2480kg (corresponding centroid height is 1200mm). The corrugated cylinder can be divided into two parts, cylindrical part and conical part. There are upper and lower end frames, bulkheads and long stringers on the carbon cylinder for the use of connecting structural panels and tanks, meanwhile, the bulkheads can also improve the radial stiffness of the cylinder.

The cylinder is manually laid with prepreg and integral formed by molding according to different laying sequence. There are 48 waves in total, and every wave is divided into three parts, wave peak, wave edge and wave valley. The section shape of the wave is shown in Fig 2.

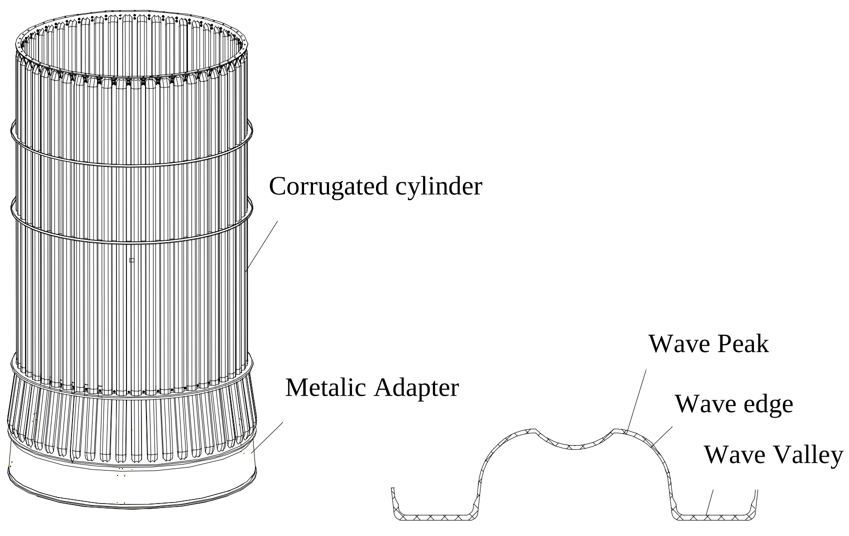

Figure 2: Schematic of central cylinder.

At the original design state, the first order transverse frequency of the center corrugated cylinder is 19.2Hz, the longitudinal natural frequency is 65.4Hz, and they meet the requirements of launch vehicle stiffness requirements for satellite with transverse frequency ≧15Hz and the longitudinal natural frequency ≧35Hz. For the design load shown in Table 3, the minimum strength margin of the corrugated cylinder is 1.2 (corresponding to Hoffman criterion). In working condition 2, the location is at the wave valley of the bottom of carbon corrugated cylinder.

Loadcase	Longitudinal load	Transverse load
Loadcase 1	4.5g	2.25g
Loadcase 2	9.15g	1.5g
Loadcase 3	-3.9g	1.5g

Table 3: Loading condition of central bearing cylinder.

Location		Minimum strength margin		
		Loadcase 1	Loadcase 2	Loadcase 3
Upper	Peak	18.7	13.7	22.7
	Side	18.7	19.1	22.7
	Trough	16.9	12.8	18.3
Middle	Peak	2.70	2.20	6.44
	Side	4.69	5.08	6.59
	Trough	4.78	3.98	8.86
Bottom	Peak	4.20	3.92	6.05
	Side	3.26	3.82	5.88
	Trough	1.60	1.18	4.86

Table 4: Strength margin of corrugated cylinder.

3.2 Optimum analysis and design

In order to further realize the structural weight reduction, multidisciplinary optimization software ESSOS and algorithms are used to optimize the ply thickness at different locations. Besides, the laying sequence has been optimized and adjusted as well for the purpose of the convenient manufacture.

The aim of the optimization is to obtain the lightest weight of the structure. The optimization constraint is that the first order natural frequency is more than 18Hz, the purpose of which is to ensure the stiffness properties of corrugated cylinder equal to the original state. The optimizing parameters are the thickness of the 0° plies and ±45° plies.

The skin of the cylinder should be divided into several parts along the axial direction and optimized separately due to the significant mass changes of the corrugated cylinder along the height direction. Thus, it is divided into three parts based on the edges of bulkheads, namely the upper, middle and lower parts. For each part, the skin can be optimized based on the wave peak, wave edge and wave valley areas. Thus there are 18 groups of optimized parameters in total. The final laminate stacking sequences are listed in Table 5 by considering the results of both numerical optimization and process optimization. Only the optimization results of the upper parts are shown here. It can be seen from the Table 5 that two groups of ±45° plies are reduced at each place of the upper part of the corrugated cylinder. Besides, four 0° plies are added at the wave edge, which make the 0° plies continuous and can simplify the manufacture.

Location		Initial stacking sequence	Optimized stacking sequence
Upper	Peak	$\pm45/\pm45/0_4/\pm45/45$	$\pm45/0_4/\pm45$
	Side	$\pm45/\pm45/0_6/\pm45/45$	$\pm45/0_4/\pm45$
	Trough	$\pm45/\pm45/\pm45/\pm45$	$\pm45/0_4/\pm45$

Table 5: Stacking sequence of central bearing cylinder.

For the above optimized center corrugated cylinder, its transverse first order frequency is 18.2Hz and its longitudinal first order frequency is 53.6Hz. Both frequencies meet the above requirements. The minimum strength margin is 0.92, which can satisfy the requirements although it's a bit lower than 1.2 at the original state, and it is also shown at the wave valley of the bottom of carbon corrugated cylinder.

Compared with the original design state, the weight of the optimized carbon cylinder can reduce about 1.3kg, and the reduction rate is around 5%.

4 PRODUCTION AND VERIFICATION OF SCALING MODEL

In order to reduce the risk of directly producing the full-size corrugated cylinder, five-wave specimens were produced based on the stacking sequence and structural type of the lower corrugated cylinder according to the composite building-block type verification logic. Then the static tests were carried out on the specimens. The aims of the tests are as follows:

1) verify the optimization results of the center corrugated cylinder;

2) verify the production method and process;

3) obtain the strains at the typical locations and failure loads to support the verification for the following full-size corrugated cylinder.

The dimension of the specimens was determined after the predictive analysis. The specimens can represent the stress states and failure modes of the full-size structures. The qualification compressive load is chosen to be 37kN for the five-wave specimens based on the above design loads listed in Table 3. Passing the test means passing the verification of the design. Failure tests were conducted after the qualification tests to obtain the maximum bearing load and failure modes.

Figure 3: Experimental setup.

For the qualification test, the load-strain curves show good linearity. The maximum strain is 1487$\mu\varepsilon$ at the typical location. The residual strain is low. The specimens have passed the tests. For the failure test, the failure morphology of the specimen is shown in Fig 4. The specimen shows entirely crushing at the transition of the wave and end frame, which correlates well with the analytical results. The corresponding stress-strain curves are shown in Fig 5.

Figure 4: Failure morphology.

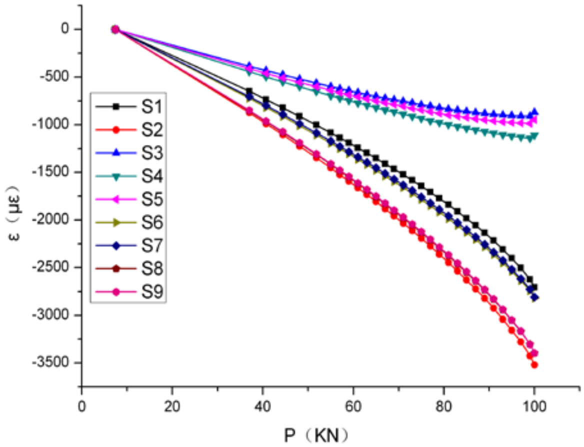

Figure 5: Stress-Strain curve.

5 PRODUCTION AND VERIFICATION OF CORRUGATED CYLINDER

5.1 Product

The weight of the full scaled carbon corrugated cylinder is 26.7kg, which is 1.3kg lower than that of the original design cylinder. The fiber volume fraction is 61.4%, which satisfies the requirement of 60±3%. The flatness of the upper and lower frames and satellite-vehicle interfaces meet the precision requirements. The non-destructive inspect indicate that the product quality is under control and do not exist defects which do not meet the requirements.

Figure 6: Composite corrugated cylinder.

5.2 Static testing

The aim of the static tests is to verify the carrying capacity of the corrugated cylinder. The carrying capacity, which is the strength requirements for the main structure of the satellite, means the load that the satellite bears under quasi-static overload condition when the satellite is launching.

Multi point coordinated loading is carried out by longitudinal and transverse joint method according to Table 3 for the static tests. The loading points is placed according to the real mass distribution of satellites. Only one concentrated loading point is determined in the longitudinal and transverse directions respectively by the collection process conducted in the lever system. The boundary conditions are clamped support at the connecting surfaces of the satellite-vehicle. Strain gages and displacement measurement system are used to monitor the stress state of the structures.

Figure 7: Loading state.

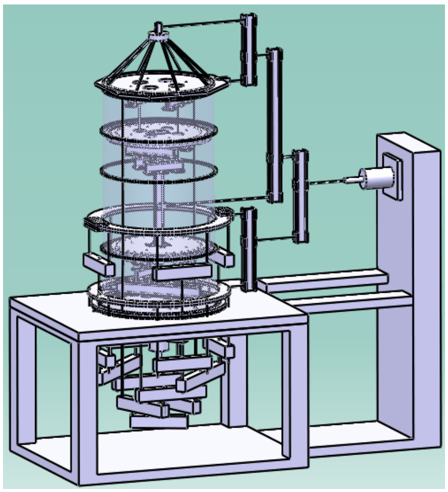

Figure 8: Loading scheme

The load-strain curves of the static tests are shown in Fig 9. It can be seen that the curves show good linearity and the residual strains are low after unloading. The deformation and the stress state of the corrugated cylinder under static test are equal to design resultes. The typical strain is 1497με at the same places for the five-wave specimens and the magnitudes of these data correlate well.

The non-destructive testing results after the static tests indicate that the corrugated cylinder has passed the performance test, which means that the structure meet the load bearing capacity required.

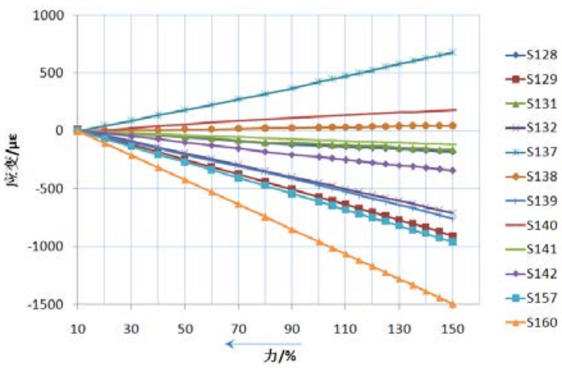

Figure 9: Load-Strain curve of typical stain gages.

5.3 Vibration testing

The aim of the vibration tests is to verify that whether the structures can satisfy the fundamental frequency requirements of the launch vehicle or not, to verify the bearing capacity of the low frequency vibration environment and to obtain the dynamic characteristic. The test level are listed in Table 6.

	Frequency	Acceptance standard	Identification standard
Longitudinal (X)	8~100	0.8g	1.2g
Transverse (Z)	8~100	0.6g	0.9g

Table 6: Parameters of vibration testing.

The real mass characteristics of the satellite (including the mass and its distribution) are simplified to reduce the test costs. The tank and propellant installed in the corrugated cylinder are simplified into counter weight. The earth panel, middle panel and anti-earth panel are simplified into rigid frames. The total weight of the satellite is 2480kg.

The vibration tests include longitudinal and transverse tests. The tests consist of characteristic level, acceptance level and qualification level. Characteristic level tests are conducted to obtain the characteristics of the structure and then are used for the fault diagnose before and after the large magnitude tests. Acceptance standard tests are conducted for the process detection during the acceptance of the products. Qualification standard tests are conducted for the verification of the product design.

Figure 10: Vibration test of central cylinder.

The first order transverse frequency is 18Hz and first order longitudinal frequency is 64Hz, which satisfy the launch requirements. The longitudinal frequency is higher than the analytical results due to the simplification of the specimen. In the transverse vibration tests, input notch has been carried out at the transverse basic frequency to prevent overloading at the root of the satellite. The notch level is 0.45g during qualification tests. The strain of the typical location after recessed treatment is 750με, which is no more than 1494με in static test. The characteristic curves correlate well before and after the identification standard tests. The corrugated cylinder has passed the vibration tests.

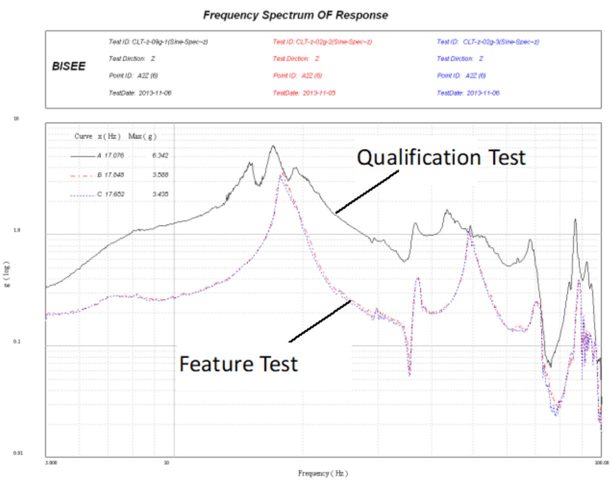

Figure 11: Acceleration response curve of typical testing point.

6 CONCLUSIONS

Design and optimization analysis, which achieve the double-optimization effect of both structure weight reduction and manufacture simplification, have been conducted to the corrugated cylinder of large satellite structure based on the novel BHM3/BS4 composite system. According to the optimization results, firstly, subcomponent specimens are produced, design parameters and feasibility of the process are verified and the typical location strains and failure modes are obtained. Then the full-size corrugated cylinder is produced and the quality of the products can meet the requirements. In the static tests and sine vibration tests, the results indicate that the products have passed the test and can satisfy the rigorous lightweight requirements of the satellite structures. The BHM3/BS4 carbon fiber composite system can be effectively applied to the spacecraft composite structures.

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