Mechanical analysis of a tip-loaded deployable truss based on shape memory polymer composite

Fengfeng Li, Liwu Liu, Linzhe Du, Yanju Liu, Jinsong Leng

Abstract

A tip-loaded deployable truss (TLD truss) with gusseted base and auxiliary support frame has been developed to carry a heavy tip load. This paper presents details in a sequence of material characterization, structure description, finite element analysis, and mechanical experiments. It uses carbon fabric reinforced cyanate-based shape memory polymer composite as the driving source to unfold the packaged truss. The glass transition temperature of the shape memory polymer composite is 195 °C. The recovery moment of the composite increases first and then decreases with the increase of the recovery ratio. Three different structural forms have been compared by modal analysis and swept sine simulations; results show that the TLD truss with a tip load of 1.3 kg has the highest stiffness. Thus it was selected and manufactured to carry out a series of experiments, including swept sine vibration, acceleration and shock tests of the packaged TLD truss, and modal testing of the deployed TLD truss. No damage was observed, indicating the TLD truss has a relatively high stiffness and could withstand the required mechanical environment.

1. Introduction

Shape memory polymers (SMPs) represent a kind of macro-molecular polymer which can transform from a temporary configuration to the original configuration under certain stimuli [1–7]. SMPs have the advantages of low density, large recoverable strain, controllable stimulus method, and flexible manufacturability of the glass transition temperature [1,2,4]. However, drawbacks of SMPs are low stiffness, low recovery force, and long recovery time [3,5,6]. Therefore, shape memory polymer composites (SMPCs) have been developed. The SMPCs generally can be divided into particles-reinforced composites according to the type of reinforcements [6–12]. The particles-reinforced SMPCs are usually used as functional materials, their fillers include carbon black [8], carbon nanotube [9,10], Ni powder [11], etc. The fiber-reinforced SMPCs are more used as structural materials due to high strength and large recovery force; their fillers include glass fiber [12], carbon fiber [13–15], and Kevlar fiber [12], etc. Taking thermal-induced SMP/SMPC as an example, a complete shape memory cycle starts from the original shape. Then the material is deformed to a temporarily new shape by an external force at a temperature above the glass transition temperature (Tg). After the deformation, the SMP / SMPC is cooled down below Tg with constraint, once the temporary shape is fixed, the external constraint is removed. Finally, the SMP/SMPC is reheated to a temperature above Tg to recover to its original shape [5,6,16]. It is the shape memory property that makes the SMP / SMPC a promising alternative to the deployment mechanism of space deployable structures.

Space deployable structure is a kind of structure which can change the configuration so as to change its size significantly [17–24]. The deployable boom is a typical example. It provides a versatile platform for a variety of payloads, such as array [18], antenna [19], propulsion ion thruster [24], etc. In general, current existing flight-heritage booms can be divided into tubular deployable booms (mass inefficient but mechanically simple) [26,27], and collapsible truss booms (mass efficient but mechanically complex) [24,28,29]. Recently, the SMP/SMPC has been introduced into the design of deployable booms [22–25]. Some of these structures have completed spaceflight experiments, some have just done ground-based verification [5,21–29]. In 2007, the deployable gravity gradient boom based on elastic memory composite (EMC, a kind of carbon fiber reinforced SMPC developed by the Composite Technology Development Inc., Lafayette, CO) was carried by FalconSAT-3 satellite to low earth orbit to verify the shape memory recovery deployment technique [23,24] The boom was designed with extensible sleeves and 120° distributed EMC laminate longerons around
the central sleeve. It was deployed and mostly stabilized the satellite in the Z-axis [25]. In 2014, Zhang et al. developed a three-longeron beam which was similar to the boom mentioned above, but its cross-sections of the same-stage sleeve were in the equal sense for reducing the friction [21,22]. In 2016, Li et al. introduced a three-longeron truss which had three sleeve rods placed in parallel for forming an equilateral triangle cross-section, and SMPC laminates overlaid the outside of sleeve rods [22]. Both the three-longeron beam and three-longeron truss had done the ground-based deployment tests and shown good characteristics of deployment in material-level without complex mechanical devices [21,22].

The challenge of the deployable truss in this paper is that it is designed with a tip load. Though the operational state of space deployable boom/truss is in microgravity or non-gravity environment where the tip load does not affect the deployment. The mechanical environment during the launch cannot be ignored since the tremendous vibration could damage the structure or even the entire launch project. In this work, the SMPC laminate characterization, including the dynamic mechanical analysis and cyclic recovery moment measurement at different recovery ratio, is firstly described in Section 2. The structural form is introduced in Section 3. Then, three structural forms have been compared in modal analysis and swept sine vibration simulation by the Patran/Nastran package in Section 4. The TLD truss with tip load of 1.3 kg is manufactured and carried out a series of experiments, including swept sine vibration, acceleration and shock tests of the packaged TLD truss, and modal testing of the deployed TLD truss. These experimental details are presented in Section 5. Finally, a conclusion is given in Section 6.

2. Material characterization

The SMPC laminate is carbon fabric reinforced cyanate-based SMPC with four layers in fiber orientation of −45°/45°. The matrix is developed by Jinsong Leng’s group [30]. The main reason for choosing the cyanate based SMP in this project is its high Tg. The reinforcement is plain weave carbon fabric CO6343B, TORAY. The manufacturing method is vacuum assisted resin infusion.

2.1. Dynamic mechanical analysis

For studying the thermo-mechanical property of the SMPC, a dynamic mechanical analysis (DMA) testing was conducted on a DMA Q800 analyzer (TA Corporation) with the dual-cantilever mode over a span of 50 mm and a frequency of 1 Hz. The temperature increased from 25 °C to 300 °C at a constant heating rate of 5 °C/min. The specimen had a dimension of 60.00 mm × 5.00 mm × 1.58 mm. The Tg is defined as the temperature corresponding to the peak of the tan delta, which is 195 °C in Fig. 1. The transition range starts from ~120 °C and stops at ~240 °C. The storage modulus is ~5.3 GPa at 30 °C, while ~308.4 MPa at 300 °C.

2.2. Recovery moment testing

The measurement of cyclic recovery moment at different recovery ratio is to obtain the change law of the recovery moment during the recovery process and to verify the deformation influence on the recovery properties. Fig. 2 presents the measurement illustration and setup. A SMPC laminate strip with original dimension of 230.00 mm × 25.00 mm × 1.58 mm was bent to a U-shape over a cylinder with the radius of r = 37.00 mm. A resistor heater with the rated voltage of 25 V and power of 30 W was stuck to the laminate. One end of the laminate was fixed to a fixture, the other end could recover freely once the electricity was turned on. The balanced temperature was 220 °C. Here we assumed the recovery process follows Fig. 2. The bending angle θ was set as the angle between the moving arm and its original line shape. The angle of the original line shape is 0°, and the angle of the U-shape is 180°. When bending angle reached 180°, 150°, 120°, 90°, 60°, 30°, 0°, a pressure sensor was placed perpendicular to the surface of the laminate at a specific point. The pressure sensor restrained the moving arm, and then the force could be detected, as shown by the red arrow in Fig. 2(a). The recovery ratio Rθ is defined in Eq. (1). The recovery moment Mθ is calculated by Eq. (2). Where the Fθ is the force obtained by the pressure sensor, l0 is the length of the arm, l0 is the original line length which equals 136.20 mm.

\[
R_\theta = \frac{180° - \theta}{180°} \times 100\%
\]

\[
M_\theta = F_\theta \times l_\theta = F_\theta \times \left(l_0 - \pi r \frac{\theta}{180°}\right)
\]

Fig. 3 demonstrates the recovery moment in every cycle firstly increases, reaches a peak at the recovery ratio of 33.34%, and then decreases to zero. The recovery force decreases all the way, the length of the arm increases linearly during the recovery process. At the beginning, the increase of the arm is more significant than the force reduction. Thus the overall performance of the moment is increase. After that, as the stored energy releases with recovery, the force decreases sharply, resulting in the moment reduction. Eventually, the recovery ratio reaches 100%, releasing all stored energy and resulting in recovery force to zero. The recovery moment decreases with the cycle increase, dropping about 18.5% in the second cycle, and 31.9% in the fifth cycle compared to the value in the first cycle, but still above 120 N/mm in the seventh cycle. The decrease might be caused by the unavoidable damage after each deformation. For having a larger recovery moment, the SMPC laminate of the TLD truss should be in its second or third deformation state during mission operation.

3. Structural form description

3.1. Description of the TLD truss

The main part of the TLD truss has inherited the deployment mechanism of the previous three-longeron beam [21,23,24] or truss [22], using multi-stage sleeves as the central extensible mast, overlaid by 120° distributed SMPC laminates outside (Fig. 4). The envelope size of the packaged truss is 490 mm × 4315 mm, and the deployed truss is 970 mm × 4310 mm. A truss with a tip load is like a billboard: a column has a plane board at the head. Similar to the wind/seismic loads on billboards, vibration of the truss in a dynamic launching environment might cause structural root fatigue. For improving the stiffness of the TLD truss, a gusseted base and an auxiliary support frame has been designed. Meanwhile, considering the fixation capability of the SMPC laminate is no longer sufficient to lock the truss in the packaged configuration under significant dynamic condition, a rod-fashioned release
device is arranged inside the sleeve. Overall, the TLD truss is composed of three stages of the main sleeves, a positioning sleeve, a rod-fashioned release device, two stages of SMPC laminates, an auxiliary support frame and a chassis, as shown in Fig. 5.

These sleeves are all hallowed cylinders with lengths and outer diameters as following, first-stage: 283.00 mm, Ø70.00 mm, second-stage: 292.00 mm, Ø60.00 mm, third-stage: 402.00 mm, Ø50.00 mm, positioning sleeve: 105.00 mm, Ø60.00 mm. Their thicknesses are 5.00 mm. The first-stage sleeve is the bottom sleeve with a gusseted base to resist the entire shear force of the cantilever. There are three gussets distributed 120° around the sleeve, shaped like a right triangle with dimensions of 50.00 mm in long leg, 29.00 mm in short leg, and 5.00 mm in thickness. The second-stage sleeve is located in the middle and the third-stage sleeve is located in the innermost. Both of them are axially movable. Spacing grooves are arranged on the interaction surfaces of the first, second and third sleeves to limit radial movement and guide the axial movement. The waist of the first-stage sleeve, the top of the second-stage and third-stage sleeves have hexagonal flanges to connect the SMPC laminates. The positioning sleeve is placed on the outside of the third-stage sleeve, and is pressed by the second and the third sleeves.

The rod-fashioned release device is designed to restrict the axial movement. It consists of a top box, a shape memory alloy frangibolt actuation [31], a rod and a chassis. The 1.3 kg top box is mounted on the hexagonal flange of the third-stage sleeve. The rod is connected in series with the frangibolt. The top end of the frangibolt passes through the baffle of the top box and is bolted at the head to adjust the locking force, which is ~2000 N in this study. The bottom end of the rod is fixed to the chassis, which is a round metal plate to mount the truss and connect the whole structure to the spacecraft. The release device directly presses the third-stage sleeve, transmitting part of the force through the positioning sleeve to the second-stage, and finally to the first-stage. Once the frangibolt is disconnected, the whole structure is released and can move in the axial direction.

The SMPC laminate is folded into a “U-shape” during the launch and ascent, and then recovers to the “stretched-shape” on orbit by heating the SMPC above Tg to provide the driving force to deploy the packaged TLD truss. There are two stages of the SMPC laminates fabricated by the
same material but different dimensions. Taking the bottom as the first-stage, the SMPC laminate has a dimension of 70.00 mm in width, 1.58 mm in thickness, 394.00 mm in the original flat length. The curved part of the “U-shape” laminate is in the middle with a radius of 65.00 mm. The dimensions of the SMPC laminate in the second-stage are 70.00 mm (width), 1.58 mm (thickness), 378.00 mm (original flat length), and 60.00 mm (radius). The SMPC laminate doesn’t recover to its original flat shape in the deployed truss, the recovery ratio is ~90%, as we need the recovery moment to insert the spring pin into the spring hole to achieve sleeve locking. Both ends of the SMPC laminate are hinged to the edges of the hexagonal flange at different sleeves.

For reducing the force on the root of the first-stage sleeve and increasing the stiffness of the whole structure, an auxiliary support frame is designed, which is composed of three columns and three rails. Each column is fixed to the chassis and connected to each other by the rail. The head of the support frame is pressed by the baffle of the top box. Therefore, most of the force is transmitted to the columns instead of the central sleeves.

3.2. Description of the other two trusses

Though the final design of the TLD truss has been provided above, it is actually optimized from the other two beams. We will describe the remaining two structures according to the TLD truss. The first one is the conventional three-longeron beam (like the structure in reference [21], hereinafter abbreviated as CTL beam) as shown in the Fig. 6(a). The CTL beam is the result of the TLD truss removing the auxiliary support frame and the gussets at the first-stage sleeve. The second is the gusset reinforced three-longeron beam (hereinafter abbreviated as GRTL beam) as shown in the Fig. 6(b). The GRTL beam is the result of the TLD truss removing only the auxiliary support frame.

4. Comparison of candidate structures by finite element analysis

4.1. Modeling

Patran/Nastran package is used to aid the design. The CTL beam and the GRTL beam are simplified into three groups: the SMPC laminate group, the sleeve group, and the release device group. In addition to these three groups, the simplified model of the TLD truss has the fourth group, the auxiliary support frame group.

For improving the computation speed and accuracy, the finite element models are constructed according to the geometry and properties of structural components (Fig. 7). Sleeves and SMPC laminates are created by shell with the Quad4 element type; columns and rails in the auxiliary support frame group are established by bars with the Bar2 element type. The locking force induced by the release device is up to 2000 N, so it can be assumed that sleeves in these structures are well compacted without relative axial or transverse movements. We ignore
the frangibolt of the release device and model the central rod with bar elements. The top box weights 1.3 kg, which means these candidate structures have already been subjected to a tip load of 1.3 kg. Besides this, the candidate structures with tip load of 2.8 kg are also investigated. The extra 1.5 kg tip load is represented by the lumped mass (0 D element) at the top box.

All components in the sleeve group and auxiliary support frame group are made of aluminum alloy, as well as the top box and chassis in the release device group. The rod in the release device group is made of titanium alloy. Their material parameters are shown in Table 1. The SMPC laminate is modeled using the laminate element. It is simplified as a symmetric cross-ply laminate, consisting of eight layers, with the specific orientation and thickness of each layer shown in Table 2. The basic mechanical parameters of each layer at room temperature are shown in Table 3. The density of SMPC is 1500 kg/m$^3$.

The connections between each sleeve are the MPC rigid which constrains motions in all directions. The short ends of the SMPC laminate are hinged to edges of the hexagon flange of the sleeve. The displacement boundary condition is to set the movement of the bolt holes on the chassis to zero in all directions.

### 4.1.1. Modal analysis

The modal analyses of candidate structures with tip loads of 1.3 kg and 2.8 kg are performed by Normal modes in the solution type. The eigenvalue extraction method is Lanczos, and the number of desired roots is 10. Since the SMPC laminate has much lower stiffness than the main metal frame of the structure, the first few orders of the natural frequency are contributed by SMPC laminate. In order to analyze the stiffness of candidate structures, the SMPC laminate group is removed. Thus, there are twelve cases in total as shown in Table 4.

4.2.1. Swept sine vibration simulation

Swept sine vibration simulation is performed by way of the frequency response in the solution type. A time-dependent load case is established with the acceleration condition in Table 5 and the displacement boundary condition above. The acceleration is applied to nodes the same as in the displacement boundary condition. The direction of acceleration is set to be X, Y, Z, respectively. The Lanczos extraction method is chosen with a frequency range of interest 5–100 Hz. The structural damping coefficient is 0.02. There are 18 cases in total: 3 (three candidates) × 2 (two tip loads) × 3 (three directions).

<table>
<thead>
<tr>
<th>Ply method of the carbon fiber reinforced SMPC.</th>
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<tbody>
<tr>
<td>No. of layer</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
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<td>5</td>
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<td>7</td>
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<td>8</td>
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</table>

### 4.2. Result and comparison

4.2.1. Modal analysis

The first six natural frequencies of the different tip-loaded structures with SMPC laminates are: the same, 27 Hz, 29 Hz, 30 Hz, 32 Hz, 33 Hz, and 38 Hz sequentially. Here we use the TLD truss with the tip load of 1.3 kg as an example. The first six mode shapes corresponding to the SMPC laminate’s swing, as presented in Fig. 8. Since the SMPC laminate is connected to the sleeve at the end, which is similar to the cantilever beam, and the SMPC laminate is relatively softer than the metal frame of the structures.

For analyzing the stiffness of the main metal frames of candidate structures, SMPC laminates are removed. Table 6 lists the first three natural frequencies for the main metal frames of candidates with different tip load weights. Fig. 9 presents the first three mode shapes of frames with the tip load of 1.3 kg, and frames with the tip load of 2.8 kg have the same first three mode shapes as frames with the tip load of 1.3 kg. The first order of natural frequency for each candidate structure is close to its second order, since the structure is approximately centre-symmetric, the first and second mode shapes are all bending of the sleeves just with direction difference. Each structure type with the tip load of 1.3 kg has a higher natural frequency than that with the tip load of 2.8 kg. For each structure type, the first two natural frequency differences between the 1.3 kg and 2.8 kg tip-loaded cases are ~20 Hz, because the added mass is at the end of the structure and the added value is the same, thus the frequency differences are close. The third mode shape is the rod swing of the release device, so the third order of natural frequency is not affected by the tip load. Comparing natural frequencies of candidate structures with the same tip load, we can find

<table>
<thead>
<tr>
<th>Material type</th>
<th>Density (kg/m$^3$)</th>
<th>Modulus (GPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloy</td>
<td>2700</td>
<td>70</td>
<td>0.33</td>
</tr>
<tr>
<td>Titanium alloy</td>
<td>4500</td>
<td>107</td>
<td>0.30</td>
</tr>
</tbody>
</table>
that the CTL beam has the lowest, while the TLD truss has the highest natural frequency.

4.2.2. Swept sine vibration simulation

Each candidate is fixed at the bottom and has the highest response at the top. A node at the top (red nodes in Fig. 7) is selected to obtain the response, and it is also where the accelerometer locates in the practical experiments in Section 5. Fig. 10 presents the results in different directions. The frequencies corresponding to the maximum response in X and Y directions are close to the first order of natural frequency shown in Table 6, except the TLD truss with tip load of 1.3 kg and 2.8 kg whose maximum responses happen at 100 Hz since the swept frequency doesn’t cover their first natural frequencies. Maximum responses in Z direction are at 100 Hz since all structures have none Z direction dominated mode shape below 100 Hz. The maximum accelerations for CTL and GRTL with tip load of 1.3 kg are slightly higher than these with a tip load of 2.8 kg, as shown in Fig. 10(a) and (b), since the resonance frequencies for 1.3 kg tip-loaded CTL and GRTL are higher than 2.8 kg tip-loaded. The maximum responses for TLD truss with the tip load of 2.8 kg are 102.7 g in X direction and 127.1 g in Y direction, which are over 4 times the response of TLD with the tip load of 1.3 kg. Comparing all structures, the TLD truss with tip load of 1.3 kg has the lowest responses in X and Y directions. Though its response in Z direction, 9.6 g, is a little bit higher than the others, it is not comparable to the response in X or Y vibration.

Besides the comparison of the maximum acceleration response, the maximum Von Mises stress is compared among these structures. The maximum stress occurs at the resonance frequency given above. Structures with the same form have the same maximum stress location.

| Table 5 | Swept sine vibration condition. |
|---------|------------------|------------------|
| Perpendicular to the mounting surface | Frequency (Hz) | Level (o-p) |
|         | Parallel to the mounting surface | Frequency (Hz) | Level (o-p) |
| Swept sine vibration 4 oct/min | 5–20 | 5 mm | 5–20 | 5 mm |
| 20–100 | 8 g | 20–100 | 8 g |

| Table 6 | List of frequencies for candidate structures without SMPC laminates. |
|---------|------------------|------------------|
| Mode | Frequency (Hz) |
|       | CTL beam | GRTL beam | TLD truss |
| Tip load | Tip load | Tip load | Tip load | Tip load |
| 1.3 kg | 2.8 kg | 1.3 kg | 2.8 kg |
| 1 | 85 | 66 | 92 | 71 | 129 | 103 |
| 2 | 92 | 70 | 98 | 74 | 131 | 106 |
| 3 | 165 | 164 | 166 | 165 | 176 | 175 |

Fig. 8. The first six mode shapes of the TLD truss, (a) The first order, (b) the second order, (c) the third order, (d) the fourth order, (e) the fifth order, (f) the sixth order.
Fig. 11 presents the locations of these candidates with the tip load of 1.3 kg. For CTL beam, the maximum stress is at the root of the second-stage sleeve in X and Y directions, while at the central rod of the release device in Z direction. For TLD truss, the location changes to the root of the support frames in X or Y direction, while at the mounting holes in Z direction. Table 7 indicates the heavier the tip load, the higher the maximum stress, because the heavy tip load reduces the whole structural stiffness. The 1.3 kg tip-loaded TLD truss has the lowest value of the maximum stress, which is far below the allowable stress 266 MPa for aluminum alloy and 213 MPa for SMPC laminate in all structures.

Though the natural frequency of GRTL beam is almost the same as that of the CTL beam, the maximum stress of GRTL beam is ~0.7 times tof the CTL beam with under the same tip load. For the GRTL beam, the loading condition of the first-stage sleeve base’s horizon plate portion between adjacent gussets can be regarded as a rectangular plate, wherein one edge is connected to the sleeve, the outer edge is free, and the left two opposite edges are supported by the gussets. The gusset transmits force induced by bending and axial moments to the sleeve. During vibration, the energy flow is disturbed by the gusset and dissipates therein. However, the root of the beam is still the weakest part when subjected to a large vibration load. The introduction of the auxiliary support frame greatly improves the stiffness of the structure. The first two natural frequencies of the TLD truss are increased by ~30 Hz compared to the GRTL truss. Because the three columns are 120° distributed around the sleeve, the formed triangular cross-section promotes the TLD truss has a higher stiffness. The auxiliary support frame is the main support of the TLD. Forces generated by vibration in various directions could be dispersed in the frame. Thus, the TLD truss with tip load of 1.3 kg is selected as the final structure.

5. Mechanical experiments of the TLD truss

5.1. Experimental setup

Vibration testing is arranged to examine the resonance frequency and response of the TLD truss under the required dynamic environment. Swept sine vibration testing was performed on an electro-dynamic vibration testing system (Fig. 12). A uniaxial accelerometer was placed at the selected point mentioned above. The truss was tested in three mutually orthogonal directions. The experimental condition is shown in Table 5. Characteristic swept sine vibration experiments with experimental condition of 5–1000 Hz, 0.2 g, 4 oct/min were carried out before and after the required-level experiments to assess the influence of vibration. Accelerometer’s responses, including curve shape, peak...
position and value were compared. By doing vibration testing, we can verify the accuracy of the FEA simulation and check whether the packaged TLD truss can withstand the required mechanical environment.

The significance of acceleration testing is to assess the rigidity of the structure when subjected to inertial forces. This experiment used a centrifuge with a diameter of 8 m. The TLD truss was installed on a pallet which was fixed on the loading platform of the centrifuge boom. Fig. 13 shows the pallet perpendicular to the centripetal axis. The acceleration force was measured in terms of g-force. It reached 10 g at a loading rate of lower than 5 g/min, and then maintained at 10 g for at least 5 min. The truss was tested in three perpendicular directions. No accelerometer was attached to the truss. The truss was checked to find out whether there was any damage after testing.

The purpose of shock testing is to measure the shock resistance ability of the TLD truss and evaluate whether the structure can withstand the required shock environment. It was performed on a drop-hammer shock testing machine in the same direction as that of the vibration and acceleration experiments. A three-axis accelerometer was stuck to the same position as in the vibration experiment (Fig. 14). The testing condition is shown in Table 8. At least three times of shock in each direction.

The modal testing of the deployed TLD truss was conducted by means of hammering (Fig. 15). The deployed TLD truss was stood on an aluminium base. An impact hammer was used to knock the truss at the second sleeve’s hexagonal flange. The accelerometer was placed on the top. A data acquisition system (DH 5922, Jiangsu Donghua testing technology Co., Ltd.) was used to collect the data for the post-processing modal software. The resonance frequencies are calculated by the Fast Fourier Transformation (FFT).

5.2. Result and analysis

5.2.1. Vibration testing

The results of the characteristic swept sine vibrations are shown in Fig. 16, where “1” and “2” represent the characteristic swept sine vibration before and after the required-level swept sine vibration. Comparing the results in each direction, the acceleration-frequency curves’ shape, peak position and value are almost the same, which means there are barely differences of the structure before and after the required-level vibration. The Fig. 16 indicates that the resonance frequencies in X direction are 128 Hz and 453 Hz, while 126 Hz and 445 Hz in Y direction, and 648 Hz in Z direction. By taking the average values of the close resonance frequencies in different directions, the first three orders of the resonance frequencies are ~127 Hz, ~444 Hz, ~648 Hz. Comparing experimental results to simulation results, it can be observed that the first resonance frequency corresponding to the first natural frequency 129 Hz in Table 6. The relative error of the measured first order of natural frequency was ~1.6%. The second and third orders of frequencies in FEM simulation haven’t been measured due to the limitation of the accelerometer’s position.

Since the swept sine vibration ended at 100 Hz, the truss did not undergo significant resonance. Experimental curves in Fig. 17 are similar to the corresponding curves in Fig. 10. Table 9 shows the comparison of swept sine vibration simulation and experimental maximum response. The maximum responses emerged at ~100 Hz. The experimental maximum responses in X, Y and Z directions were 28.0 g, 22.2 g and 8.2 g, respectively. The difference of the maximum response between the experiment and the simulation was 2.3 g in X, 0.5 g in Y and 1.4 g in Z direction. This is acceptable and inevitable due to the simplification of the finite element model and experimental error. No damage was observed after vibration experiments.

5.2.2. Acceleration testing

Acceleration testing was carried out in three orthogonal directions by changing the structural mounting platform to different directions toward the centripetal axis. The acceleration reached 10.5 g after 3 min and held steadily for about 5.2 min (Fig. 18). During the testing, no relative motion was observed between the truss and the platform. The truss’s characteristics, including geometry, appearance, connection, resistance, were checked after testing, no electrical or mechanical damage occurred during testing.

Fig. 10. Results of swept sine vibration simulation in different directions, (a) the X direction, (b) the Y direction, (c) the Z direction.
5.2.3. Shock testing

Upon shocking, the TLD truss had a rigid motion with the table, no obvious jitter of the structure was observed. Average values of the maximum acceleration in time domain upon different directions were listed in Table 10. The response along the shocking direction was the largest in X and Y shocking cases, the X-axis response in the X shocking case was 494 g, and the Y-axis response in the Y shocking case was 500 g. Fig. 19(a) and (b) indicated that the shock response spectrum curves in X and Y shocking cases were similar since the truss was axisymmetric on the mounting platform. The stiffness in the Z direction is the largest. Thus the response in the Z shocking case was relatively small. No deformation and damage were found after each shocking, the resistance of every resistor heater remained unchanged before and after the testing.

5.2.4. Modal testing of the deployed TLD truss

After deployment, the TLD truss would not be subjected a severe vibration condition like the packaged truss. The deployed TLD truss stretched like a cantilever. Fig. 20 demonstrates the response of the modal test of the deployed truss in frequency domain. The first three order of resonance frequencies corresponding to the peaks of the curve are ~5.37 Hz, ~8.58 Hz, ~11.00 Hz. The largest amplitude occurs at the first order of resonance frequency, 5.37 Hz, which is due to the bending mode response.

6. Conclusion

The TLD truss is a carbon fabric reinforced cyanate-based SMPC laminate drove truss which can deploy from the packaged configuration to the deployed configuration. Its deployment mechanism is in

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**Table 7**
The maximum Von Mises stress in different direction.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Maximum Von Mises stress (MPa)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td>CTL beam with tip load of 1.3 kg</td>
<td>357</td>
</tr>
<tr>
<td>CTL beam with tip load of 2.8 kg</td>
<td>506</td>
</tr>
<tr>
<td>GRTL beam with tip load of 1.3 kg</td>
<td>258</td>
</tr>
<tr>
<td>GRTL beam with tip load of 2.8 kg</td>
<td>369</td>
</tr>
<tr>
<td>TLD truss with tip load of 1.3 kg</td>
<td>26</td>
</tr>
<tr>
<td>TLD truss with tip load of 2.8 kg</td>
<td>132</td>
</tr>
</tbody>
</table>

Fig. 11. Locations of the maximum Von Mises stress for different structural forms with tip load of 1.3 kg in different directions.

Fig. 12. Vibration testing in the Z direction (an accelerometer is placed on the top box).
material-level, without complex mechanical driving components. The 
Tg of the matrix is 195 °C. The recovery moment of the composite in-
creases firstly, reaching a peak at the recovery ratio of 33.34%, and 
then decreases to zero. For getting high stiffness, the design of the 
structure has gone through three stages: CTL beam, GRTL beam, and 
TLD truss. Their dynamic characteristics have been compared by finite 
element analysis simulation. The CTL beam uses sleeves as the central 
extensible mast, and SMPC laminates overlaid outside the mast as the 
driving source. For strength the root of the CTL beam, a gusset 
reinforced base is arranged at the GRTL beam. The natural frequency of 
the GRTL beam slightly increases compared to the CTL beam, but still 
less than 100 Hz at the first mode of the main metal frame. Then the 
introduction of the auxiliary support frame in the TLD truss sig-
ificantly improves the whole structure’s stiffness, reaching 129 Hz at

---

**Table 8**

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 ~ 1500</td>
<td>+6 dB/oct</td>
</tr>
<tr>
<td>1500 ~ 4000</td>
<td>1600 g</td>
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</tbody>
</table>

---

**Fig. 13.** Image of the acceleration testing (the mounting platform is perpendicular to the centripetal axis, the truss is covered with multi-layer insulation).

**Fig. 14.** Image of the shock testing in the Z direction (a three-axis accelerometer is placed on the top box, the truss is covered with multi-layer insulation).

**Fig. 15.** Modal testing of the deployed TLD truss, (a) schematic of the testing system, (b) setup of the deployed truss.

**Fig. 16.** Results of characteristic swept sine vibrations in X, Y, Z directions.
the first mode for the metal frame with the tip load of 1.3 kg, and 103 Hz for the one with the tip load of 2.8 kg. Swept sine vibration simulation shows the 1.3 kg tip-loaded TLD truss has the lowest responses in X and Y directions, and the lowest value of the maximum Von Mises stress among these structures. Thus, we chose the TLD truss with the tip load of 1.3 kg as the final selection to conduct practical experiments. Vibration testings indicates that the 1.3 kg tip-loaded TLD truss could endure 8 g swept sine vibration. And the first resonance frequency is ~127 Hz, showing good consistency with the simulation results, 129 Hz. Results of the acceleration testing showed that the TLD truss could withstand the 10 g acceleration in three orthogonal directions. The shock testing, with the level of 1600 g, demonstrated that the truss had a good shock resistance. The modal test of the deployed truss by hammering demonstrates that the first resonance frequency the truss is ~5.37 Hz. No deformation and damage were found after these testings. In all, the TLD truss has a relatively high stiffness and can withstand the required mechanical environment. It could be used as the

<table>
<thead>
<tr>
<th>Vibration direction</th>
<th>The maximum response of the selected point</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Simulation</td>
</tr>
<tr>
<td>X</td>
<td>100 Hz @ 25.7 g</td>
</tr>
<tr>
<td>Y</td>
<td>100 Hz @ 22.7 g</td>
</tr>
<tr>
<td>Z</td>
<td>100 Hz @ 9.6 g</td>
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</table>

Fig. 17. Results of swept sine vibration testing in X, Y, Z directions.

Fig. 18. The acceleration testing control plot.

Table 9
Comparison of swept sine vibration simulation and experimental maximum response.

<table>
<thead>
<tr>
<th>Shocking direction</th>
<th>The maximum acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>494</td>
</tr>
<tr>
<td>Y</td>
<td>470</td>
</tr>
<tr>
<td>Z</td>
<td>251</td>
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</tbody>
</table>

Fig. 19. Shock response spectrum of the three-axis accelerometer in different shocking direction, (a) X shocking, (b) Y shocking, (c) Z shocking.

with the tip load of 1.3 kg as the final selection to conduct practical experiments. Vibration testings indicates that the 1.3 kg tip-loaded TLD truss could endure 8 g swept sine vibration. And the first resonance frequency is ~127 Hz, showing good consistency with the simulation results, 129 Hz. Results of the acceleration testing showed that the TLD truss could withstand the 10 g acceleration in three orthogonal directions. The shock testing, with the level of 1600 g, demonstrated that the truss had a good shock resistance. The modal test of the deployed truss by hammering demonstrates that the first resonance frequency the truss is ~5.37 Hz. No deformation and damage were found after these testings. In all, the TLD truss has a relatively high stiffness and can withstand the required mechanical environment. It could be used as the
extension shelf for various components, such as the antenna, space probe, tip mass of the gravity gradient boom, etc.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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