The 8th TSME International Conference on Mechanical Engineering
12-15 December 2017
Bangkok, Thailand

AMM0008

Evaluation of tensile strength and consideration of the rope structure of net for super-pressure balloon

R. Tanaka[1],*, T. Matsuo[1], Y. Saito[2], D. Akita[3], K. Nakashino[4], and K. Goto[2]

[1] Department of Mechanical Engineering, School of Science and Technology, Meiji University, 1-1-1 Higashimita, Tama, Kawasaki, Kanagawa, 214-8571, JAPAN
[2] Japan Aerospace Exploration Agency, 3-1-1 yoshinodai, chuo, Sagamihara, Kanagawa, 252-5210, JAPAN
[3] Department of Transdisciplinary Science and Engineering, Tokyo Institute of Technology, 2-12-1 Oh-okayama, Meguro, Tokyo, 152-8550, JAPAN
[4] School of Engineering, Tokai University, 4-1-1 Kitakinme, Hiratsuka, Kanagawa, 259-1292, JAPAN

* Corresponding Author: ce62039@meiji.ac.jp

Abstract. Super-pressure balloons which enable long duration flights have been developed to overcome the problem of high cost of artificial satellites. We have been studying super-pressure balloons which have film structures covered with nets of high tensile ropes. The strength of the net is important to sustain the super-pressure; however, a detailed experimental investigation has not yet been carried out. The purpose of this study is to evaluate rope fracture strength to verify its applicability for a super-pressure balloon and to verify the mechanism that limits its strength. The net is a mesh of ropes and the rope is made of twisted two strands, which consist of many thin fibers. To achieve this objective, tensile tests were carried out for a single fiber and rope. The tensile strengths of a single fiber and rope were lower than that of the bulk specimen; the strength of the rope was higher than the required strength. Next, tensile test was carried out by changing the twist angle to study their relationship. A normal twist angle was 18.3°. The greater the difference in the normal twist angle, the lower the strength of the rope. We assumed that there is a drop in the strength of the rope because a twisted rope has a torque which produces a twist back force and cuts the fiber. Next, numerical simulation was carried out to confirm this assumption. Three pitch lengths of rope models were loaded with 200 N of force. Results from the analysis shows that there is high stress between strands, and the rope turned to twist back. Therefore, it was assumed that the rope has a torque and breaks torsional balance, which cuts the fiber.

1. Introduction

Many artificial satellites have been launched for atmospheric observation and scientific experiments. However, the costs of running artificial satellites after they have been launched are high. To overcome the problem of high costs, scientific observation balloons that can fly at high altitudes for long periods of time have been developed. The super-pressure balloon is one of them, which can overcome the buoyancy fluctuations between day and night. It enables experiments at low cost, long duration flights at constant high altitudes, and new monitoring with high accuracy. Several research institutes have developed super-pressure balloons with thin film and many ropes [1-3]. The Japan Aerospace Exploration Agency and some Japanese institutes have developed super-pressure balloons with a diamond-shaped net in order to overcome the problems with conventional balloons, such as heavy weight and large mass. This type of balloon can withstand internal pressure because its film structure is covered with a diamond-shaped net and various experiments for practical applications can be conducted [4-6]. However, the strength of the net and rope have yet to be investigated in detail. The purpose of this study is to evaluate the fracture strength of a rope to verify its applicability in super-pressure balloons and to determine its behavior under loading conditions. Tensile tests on ropes and single fibers were carried out. Next, finite element method (FEM) analysis was conducted and compared with experimental results. From these results, the strength of the ropes and their behavior under loading conditions were evaluated.

2. Structure of super-pressure balloon with a diamond-shaped net

2.1. Material and structure of rope

The cover net for the super-pressure balloon is made of several polymer ropes. Figure 1 shows the structure of the rope used in this study. The balloon's rope was formed by twisting two strands consisting of many thin fibers made from polyarylate. Polyarylate is a liquid crystal polymer and high-performance fiber with a density of 1.40 kg/m^3, tensile strength of 3.01 GPa, and Young's modulus of 104.3 GPa in bulk material [7][8]. The average diameters of a single fiber, strand, and rope are 25.0 μm, 623 μm, and 966 μm, respectively. These diameters were measured with an optical microscope.

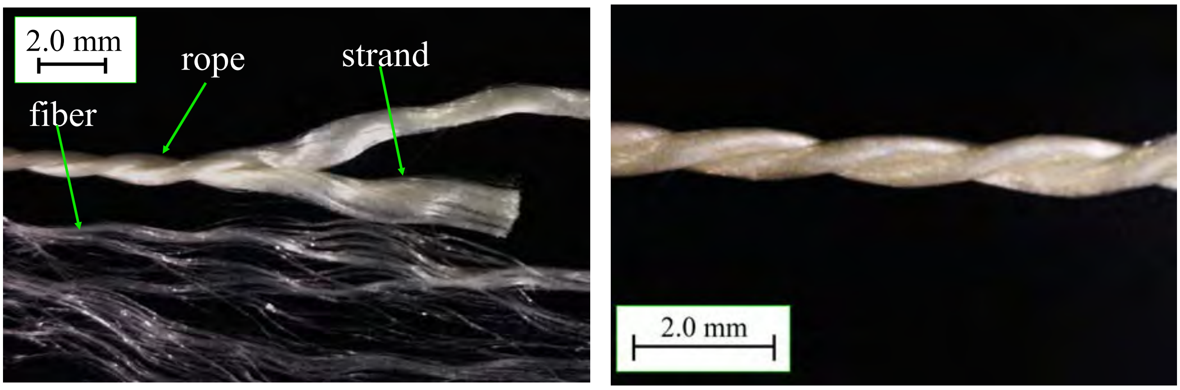

Figure 1. Components of a rope (left) and twisted rope (right).

2.2. Structure of balloon and weight reduction

Figure 2 shows the fully inflated super-pressure balloon. The balloon was inflated by internal pressure, and its surface is made up of a 10- or 20-μm-thick polyethylene film covered by a diamond-shaped net. The meshes of the rope have no-knots so as not to damage the film as shown in Figure 3.

This structure has a lobed-pumpkin shape, the film overhangs among the ropes, as shown in Figure 4 [9]. The forces acting on the film and rope are expressed by equations (1)(2), where T_{film} is the tension on the film, R_{local} is the local curvature radius of the film, and Δp is the internal pressure. T_{rope} is the sum of tensions generated on the ropes and $R_{balloon}$ is the equatorial radius of the balloon [9].

$$T_{film} = \Delta p R_{local} \quad (1)$$
$$T_{rope} = \pi (R_{balloon})^2 \Delta p \quad (2)$$

By equation (1), decreasing the size of R_{local} reduces to the tension on the film. This is made possible by the smaller size of the mesh of ropes. The force of the rope, obtained by the radius of the balloon and pressure, is not related to the local curvature radius of the film. Thus, the tension on the rope and film do not affect each other; the thin and light film can withstand pressure that leads to the reduced weight of the balloon. The ultimate goal is to fly a balloon with a volume of 300,000 m^3 to an altitude of 37 km while mounted with 1 t of equipment. The required load per rope is 59 N and the pressure is 100 Pa [4].

Figure 2. Super-pressure balloon(left) and balloon's surface(right)

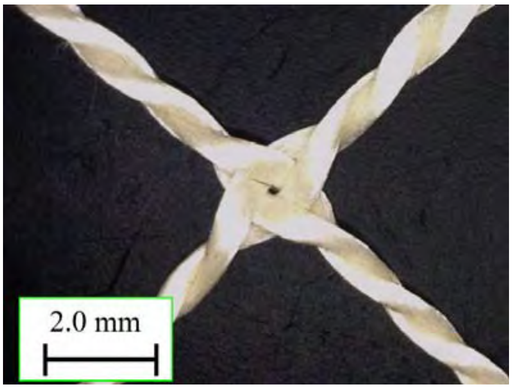

Figure 3. Mesh of rope

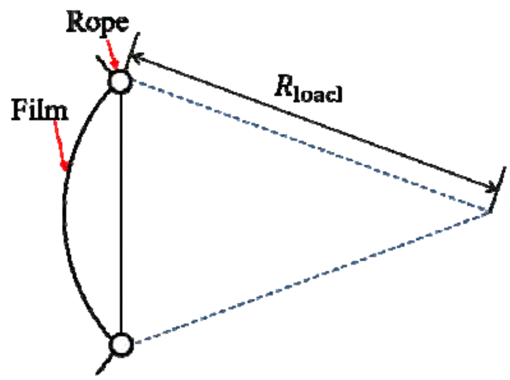

Figure 4. Protruding film from between ropes

3. Tensile strength of rope and fiber

First, tensile tests were carried out on a single fiber and rope to evaluate their strength. Tests on the fiber followed the JIS L1069 standard [10], and the edge of the rope was protected. The edge of the rope was folded back and the gripping portion was made. The tests were carried out at a speed of 2 mm/min and repeated ten times. Figure 5 shows the stress–strain curve of the rope and single fiber. Here, tensile strength was normalized by using the strength of bulk material of polyarylate. As a result, the strengths of fiber and rope were 81% and 45% of the bulk specimen, respectively. The tensile strengths of a single fiber and rope were higher than required. However, these strengths were lower than that of the bulk specimen.

After the tensile test, the damage observed on fibers, as shown in Figure 6, which was caused by the structure of the rope. Next, tensile tests of the rope with a different twisted angles were carried out at a speed of 2 mm/min. The twist angle of rope was 18.3°; the tests were carried out in both of the plus and minus directions. As a result, the difference increased as the breaking load decreased, as shown in Figure 7.

When the twist angle increased, the contact area between ropes increased and it was assumed that wearing of the fibers was caused by friction between ropes. Another reason for the reduced strength was assumed to be twisting torque. When the tensile strength was applied to the rope, it was reported that twisting generated torque that attempted to twist it back [11].

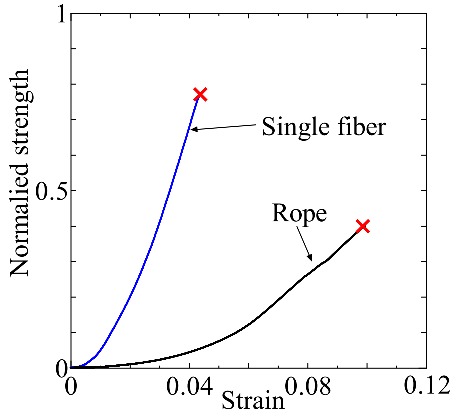

Figure 5. Stress–strain curve of polyarylate

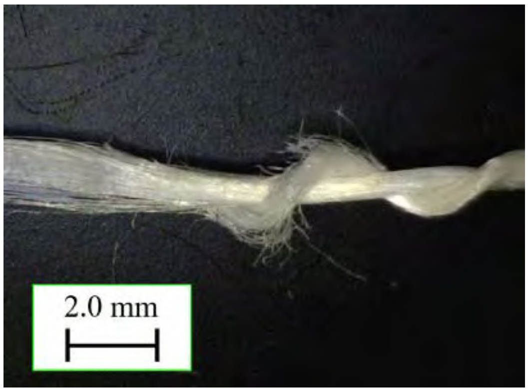

Figure 6. Surface photograph of fractured rope after the test

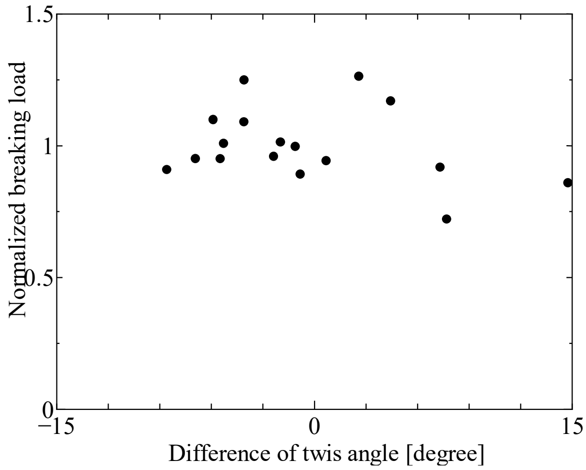

Figure 7. Relations of tensile strength and twist angle

4. FEM simulation

To determine the reason for the weak tensile strength of the rope, numerical simulations were carried out by FEM analysis. Strand models with three pitch lengths were developed; the diameter and length of the strands were 0.623 mm and 10.5 mm, respectively. The models were loaded along the rope axis with a force of 200 N while the other side was fixed. The coefficient of friction was 0.02. The density of the rope model was 1.40 kg/m^3 and Young's modulus was 104.3 GPa. The material was set as isotropic material. The results of the analysis, shown in Figure 8, indicate that there was high stress at the contact points of the strands and the rope turned to twist back. Under this condition, the apparent stress on the rope was 707.3 MPa, and the maximum principal stress was 1724 MPa, or 2.43 times the apparent stress. Therefore, a tensile strength value from the experiment multiplied by 2.43 in the tensile strength from the experiment is close to the strength of the bulk specimen.

Thus, at the contact part, the strength of the rope was equal to that of the bulk specimen. The reasons for the reduced strength were the local friction of ropes and the twisting torque caused by structure of the rope.

Table 1. Simulation conditions

Material	Polyarylate	Isotropic material	
Young's modulus	104.3 GPa	Density	1.40 kg/m^3
Diameter of strand	0.623 mm	Force	200 N
Total elements	12102	Length of rope	10.5 mm
Total nodes	24520	Friction coefficient	0.02

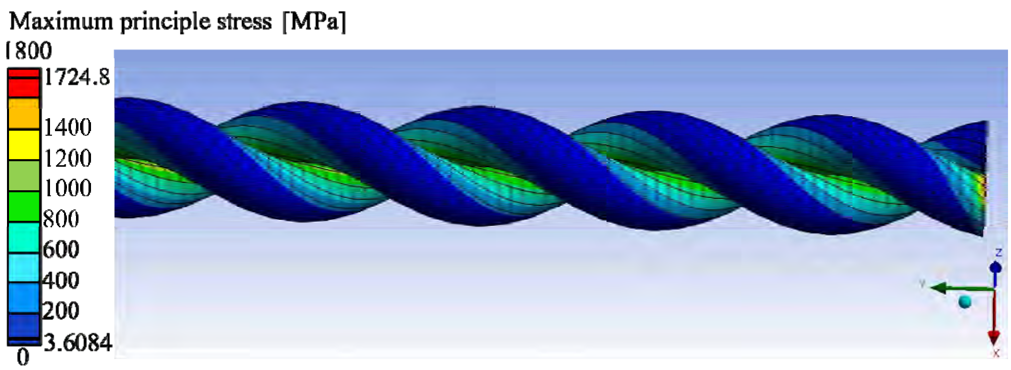

Figure 8. Distribution of principle stress by FEM analysis.

5. Conclusion
In this study, the strength of the rope for a super-pressure balloon with a diamond-shaped net was evaluated. The tensile strength of rope was first measured. The tensile strengths of a single fiber and rope were higher than required. However, these strengths were lower than that of the bulk specimen. The reason for this was determined by numerical simulation. FEM simulation results confirmed that the rope produced a torque that can twist it back, which can cut the fibers. At the contact part, the rope showed a strength equal to that of the bulk specimen.

Acknowledgement
This work was supported by JSPS KAKENHI Grant-in-Aid for Scientific Research(A) 17H01352.

References

[1] Cathey H M 2015 *Proceedings of the AIAA Balloon Systems Conference (Dallas)* (Reston:VA/AIAA)
[2] Yajima N, et al 2001 *Journal of Aircraft* **38**(4) pp738-744
[3] Venes S, et al 2014 *Proceedings of 40th COSPAR Scientific Assembly(Moscow)* (Paris:Ile-de-france /COSPAR)
[4] Saito Y 2016 *Proceedings of the 30th Atmospheric Science Symposium(Sagamihara)* ˜- 4(Sagamihara : Kanagawa/JAXA,ISAS)
[5] Saito Y, et al 2014 *JAXA-RR-13-011* pp35-60
[6] Saito Y, et al 2016 *the Proceedings of the 16th Space Science Symposium(Sagamihara)* pp1-7 (Sagamihara : Kanagawa/JAXA,ISAS)
[7] Yamamoto Y 2006 *Journal of the Japan Research Association for Textile End-Use* **47** (9) pp 520-523
[8] Nakagawa J 2003 *Journal of Textile Engineering* **56** (5) pp210-216
[9] Saito Y, Matsuzaka Y, Mizuta E, Shoji Y, Matsushima K and Tanaka S 2011 *JAXA-RR-10-013* pp25-40
[10] JIS L 1069 Tensile strength tests of natural fibers
[11] Tanaka K and Morohashi Y 1983 *Journal of Structural and Construction Engineering* 58 pp153-154