Experimental and Numerical Study of Structural Strength of Flare-Type Membrane Aeroshell with Inflatable Ring

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In order to support various future activities using spacecrafts, we need to develop a re-entry system which is useful, safe and low-cost. We have studied the structural strength of an inflatable aeroshell, which is a novel re-entry system currently under development within JAXA. In this paper, we investigate the structural strength characteristics of the inflatable aeroshell with respect to its configuration, scale effect and initial out-of-plane deformations. The investigations are carried out by both numerically and experimentally; the results are in good agreement with each other and will benefit efficient structural design of the aeroshell in a future development.

Key Words: Membrane Structure, Re-Entry System, Aeroshell, Buckling

Nomenclature

- \( d \): torus tube diameter
- \( D \): aerodynamic force
- \( E \): Young’s modulus
- \( p \): torus differential pressure
- \( r \): torus outer radius
- \( S \): torus scale rate
- \( \theta \): angle of flare
- \( t \): time
- \( t \): film thickness
- \( V \): wind velocity
- \( \nu \): Poisson’s ratio

Subscripts

- \( t \): torus
- \( f \): flare

1. Introduction

In this paper, we describe the numerical and experimental investigations of the structural strength of the inflatable aeroshell designed for a re-entry mission into the Earth. The inflatable aeroshell dealt with in this paper will be reliable and low-cost space transportation system which is different from either a capsule type or a wing type \(^1,2\). Recently those systems are developed in a variety of research institutions, for instance, NASA, ESA and JAXA.

The inflatable aeroshell is composed of three parts as shown in Fig.1. When the inflatable aeroshell re-entries into the Earth, an inflatable torus and thin membrane flare are expanded from a capsule and then the inflatable aeroshell is decelerated since it receives large aerodynamic forces because the cross section area of the system is significantly enlarged.

Our system’s merits are that the inflatable aeroshell is easily enlarged and the weight of the system is lighter compared to other systems as proposed by NASA or ESA because whole inflatable aeroshell flare is made of only thin membrane and required inflatable structure is minimized. In this system, in contrast to those proposed by NASA or ESA, the main structure component to resist to the aerodynamic forces is the inflatable torus alone; the strength of thin membrane flare part is not expected to have enough strength. Thus, the total structural strength of the system is dominated by the inflatable torus alone. In view of this structural characteristics, we carried out low-speed wind tunnel test and nonlinear finite element analysis to determine whether the inflatable torus has enough structural strength during the free flight.

Fig. 1. Schematic sketch of the proposed inflatable aeroshell.

2. Experimental Facility and Method

2.1. Test facility

We carried out a series of low-speed wind tunnel tests in order to investigate the structural strength of a variety types of inflatable aeroshell models. The test section of low-speed wind tunnel is 6.5m x 5.5m and the maximum velocity is 70 m/s.

In the wind tunnel tests, we focused on the investigation of the structural strength of the aeroshell models of which size are comparable to real-scale model used in the re-entry
experiment carried out in 2012 using a sounding rocket. In table 1, we summarize the primary conditions in the wind tunnel tests and the sounding rocket experiment. In the wind tunnel tests, we determine the range of wind velocities so that the dynamic pressure applied to the aeroshell is comparable to the real scale conditions. As a result, dimensionless numbers such as Mach number and Reynolds number are different from those in the real scale conditions. However, our primary objective in the wind tunnel tests is the investigation of the relation between the structural strength of the aeroshell and the applied total drag, and even with the above differences this relation can be clarified with the wind tunnel tests as far as the coupled fluid-structure interactions are not dominant. When the airflow around the aeroshell is of particular interests, it is necessary to suit these dimensionless numbers.

Table 1. The Comparison of the atmospheric conditions between the low-speed wind tunnel test and the sounding rocket experiment.

<table>
<thead>
<tr>
<th>Test conditions</th>
<th>Real scale conditions (Sounding rocket experiment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air density $\rho$ [kg/m$^3$]</td>
<td>1.23</td>
</tr>
<tr>
<td>Kinematic viscosity $\nu$ [m$^2$/s]</td>
<td>$1.46 \times 10^{-5}$</td>
</tr>
<tr>
<td>Velocity $V$ [m/s]</td>
<td>5 - 45</td>
</tr>
<tr>
<td>Characteristic length $L$ [m]</td>
<td>1.2</td>
</tr>
</tbody>
</table>

2.2. Test system
The setup of the wind tunnel tests carried out in 2012 is shown in Fig. 2.

Fig. 2. Set up of the low-speed wind tunnel experiments in 2012.

Internal pressure of the inflatable torus was controlled by gas supply system that was equipped with outside of the inflatable aeroshell model. Internal pressure of the inflatable torus was measured by a differential pressure meter which was located inside the capsule as depicted in Fig. 2. A six component wind tunnel balance was used for the measurement of aerodynamic forces applied to the inflatable aeroshell models. The inflatable aeroshell model shown in Fig. 2 has backup membrane part as will be described in the next subsection.

2.3. Test models
We carried out a series of wind tunnel tests with four types of inflatable aeroshells that were different in shape, torus outer radius $R$ and torus tube diameter $d$ from each other as shown in Fig. 3. The specification of four types of aeroshell model and the experimental conditions of the low-speed tunnel tests in 2010, 2011 and 2012 are shown in Table 2, including parameters of reinforcing layer of the membrane of the torus, initial out-of-plane deformations and torus scale rate $S$, which will be defined in 2.4.4. Scale parameters for the models in Table 2 are comparable to a full-scale model used in a preliminary re-entry experiment carried out in 2012 using a sounding rocket. As will be described in the remaining part of the paper, we conjecture the factor $S$ significantly affects the structural strength of the inflatable aeroshell.

As shown in Figs. 4 and 5, all the models used in the wind tunnel tests has backup membranes located on the rear side of the aeroshell. The backup membranes are tensioned by the rim torus when the torus is inflated with internal pressure, and as a result, the backup membranes keep the hub capsule be advanced from the rim torus against the gravitational force even when no aerodynamic pressure is applied.

Table 2. The specification of four types of aeroshell model and the experimental conditions of the low-speed tunnel tests in 2010 and 2011.

<table>
<thead>
<tr>
<th>Year (Sounding rocket)</th>
<th>Torus outer radius $R$ [m]</th>
<th>Torus tube diameter $d$ [m]</th>
<th>Torus configuration</th>
<th>Reinforcing layer</th>
<th>Initial out-of-plane deformations</th>
<th>Torus scale rate $S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 (Sounding rocket)</td>
<td>0.60</td>
<td>0.10</td>
<td>Circle</td>
<td>Reinforced</td>
<td>Small</td>
<td>0.167</td>
</tr>
<tr>
<td>2010 (Experimental)</td>
<td>0.60</td>
<td>0.10</td>
<td>Circle</td>
<td>Nominal</td>
<td>Large</td>
<td>0.167</td>
</tr>
<tr>
<td>2011 (Experimental)</td>
<td>0.60</td>
<td>0.10</td>
<td>Circle</td>
<td>Reinforced</td>
<td>Small</td>
<td>0.167</td>
</tr>
<tr>
<td>2012 (Experimental) #00</td>
<td>0.60</td>
<td>0.10</td>
<td>Circle</td>
<td>Reinforced</td>
<td>Large</td>
<td>0.167</td>
</tr>
<tr>
<td>2012 (Experimental) #01</td>
<td>0.60</td>
<td>0.10</td>
<td>Dodecagon</td>
<td>Reinforced</td>
<td>Small</td>
<td>0.167</td>
</tr>
<tr>
<td>2012 (Experimental) #03</td>
<td>1.175</td>
<td>0.10</td>
<td>Dodecagon</td>
<td>Reinforced</td>
<td>Small</td>
<td>0.085</td>
</tr>
<tr>
<td>2012 (Experimental) #04</td>
<td>1.250</td>
<td>0.15</td>
<td>Dodecagon</td>
<td>Reinforced</td>
<td>Small</td>
<td>0.120</td>
</tr>
</tbody>
</table>

Fig. 3. Four types of inflatable aeroshells.
2.4. Structural strength experiments

2.4.1. Experimental procedure

We carried out the structural strength experiments of the inflatable aeroshell models according to the procedure as described below.

1. An appropriate amount of gas is injected into the inflatable torus.
2. Start the operation of the wind tunnel, and keep the wind-velocity to be a prescribed constant value.
3. Internal pressure of the inflatable torus is decreased while the wind-velocity is kept constant.
4. Record the internal pressure when the inflatable aeroshell is collapsed.
5. After the collapse, the wind velocity is gradually decreased.
6. Internal pressure of the inflatable torus is again increased to the point that the inflatable aeroshell configuration is recovered to the desired normal state.

We repeated (2)-(6) procedures to investigate the correlation between the aerodynamic force $D$ [N] and the torus differential pressure $p$ [kPa] at which the torus part collapses (Fig. 6).

It should be mentioned here that even without the aerodynamic force $D$ [N], the flare part assumes designed conical shape with an inclined angle of 70 [deg]. This is because an appropriate amount of initial tension is introduced in the flare membrane by tensile forces caused by inflated torus along with the backup membranes located on the rear side of the aeroshell.

2.4.2. Effect of initial out-of-plane deformation

We compared the structural strength of the three models, each of which has different amount of initial out-of-plane deformations that were mainly resulting from manufacturing errors.

The amount of initial out-of-plane deformations are quite significant in some models as shown in the right side figure of Fig. 7 which represents an inflated shape of an inflatable aeroshell model with no aerodynamic pressure applied.

The relation between torus differential pressure $p$ [kPa] versus the aerodynamic pressure $D$ [N] when the inflatable aeroshell collapsed is shown in Fig. 8. In the figure, the experimental results obtained in 2010 are also presented in addition to those obtained in 2011’s wind tunnel tests. Three interpolated lines are also plotted in the figure; in the regions below these lines, the inflatable aeroshell models are structurally stable, or no collapse phenomena occurs. More specifically, a line with larger inclination means that the corresponding model is structurally more stable.
As shown in Fig. 8, we found that the structural strength of the model used in 2011’s experiments is stronger than those used in 2010’s experiments. This is because the model used in 2011 has smaller amount of initial out-of-plane deformations; on the other hand, the model used in 2010 has larger amount of initial out-of-plane deformations. In addition, we found that the structural strength of the model used in 2011’s experiments is also stronger than model #00 (experimental) because model #00 has larger amount of initial out-of-plane deformations. The results indicate that the parameter of initial out-of-plane deformations greatly affect strength of the inflatable aeroshell.

2.4.3. Effect of torus configuration

We compared three models of different torus configuration in order to investigate whether the torus configuration affects the structural strength of the inflatable aeroshell. The comparison includes the results obtained in the low-speed wind tunnel tests carried out in 2011.

As shown in Fig. 9, we found that structural strength of model #01 (experimental) with dodecagonal torus configuration is stronger than structural strength of #00 (experimental) with circular torus configuration because the inclination of the approximate line for the model #01 (experimental) is larger than that for the model #00 (experimental). However, this difference does not seem to be resulting from the difference in the torus configurations because the two models also have different amount of initial out-of-plane deformations. In fact, the structural strength of the model used in 2011 experiment (green line in Fig. 9) is almost the same to that of the model #01 in spite of the fact that the two models has different torus configuration. The results indicate that the amount of initial out-of-plane deformations is a primary factor dominating the structural strength of the inflatable model and that the difference in torus configuration has almost no effect for the structural strength of the inflatable aeroshell.

2.4.4. Effect of torus scale rate

We have carried out a series of wind tunnel tests using various types of inflatable aeroshell models of which torus size and entire model size are relatively different. In order to investigate this ‘scale effect’, we define the torus scale rate \( S \) by the following equation, where \( d \) [m] denotes the torus tube diameter and \( R \) [m] the torus outer radius, respectively in Fig. 10.

\[
S = \frac{d}{R} \tag{1}
\]

\( S \) [-]: torus scale rate
\( d \) [m]: torus tube diameter
\( R \) [m]: torus outer radius

Fig. 10. Schematic sketch of the defined torus scale rate.

According to Eq. (1), the torus scale rate \( S \) will be smaller if the torus outer radius \( R \) [m] is larger with the same torus tube diameter \( d \) [m].

The relation between torus differential pressure \( p \) [kPa] versus the wind-velocity \( V \) [m/s] when the inflatable aeroshell collapsed is shown in Fig. 11. We compared the results of the three models with different torus scale rate \( S \). Regarding the model #03, we could not determine the distinct collapse points, because the structural strength of the model is quite weak, and the model was gradually collapsed instead of sudden collapse.

Fig. 11. Structural strength of experimental models with different torus scale rates.
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As shown in Fig. 11, we found that the structural strength of 
#01 (experimental) with scale rate of $S=0.167$ is stronger than
those of #04 (experimental) with scale rate of $S=0.120$
because approximate curve-slope of #01 is steeper than slope
of #04. The results indicate that the inflatable aeroshell model
with large torus scale rate $S$ has large structural strength.

2.4.5. Comparison of collapse configurations

Typical collapse deformations of each model are shown in
Fig. 12.

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3.2. Effect of torus configuration

This subsection describes numerical results that were carried out for the purpose of investigating the effect of torus configuration to the structural strength of the inflatable aeroshell. Also, we investigate the effect of the variation of flare’s film thickness to the structural strength of the inflatable aeroshell. In Table 3 and Table 4. We also investigate the effect of the variation of flare’s film thickness to the structural strength of the inflatable aeroshell. In Table 3 and Table 4.

Table 3. Material properties of numerical model (flare’s film thickness of 0.05 [mm]).

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<tr>
<th>Torus</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Film thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0.3</td>
<td>0.3</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 4. Material properties of numerical model (flare’s film thickness of 0.15 [mm]).

<table>
<thead>
<tr>
<th>Torus</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Film thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0.3</td>
<td>0.3</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Fig. 14. Number of iteration and torus differential pressure for wind velocity of 30 m/s.

Fig. 16. Numerical results for models with different torus configurations (flare’s thickness of 0.15 [mm]).

As shown in Fig. 15, when film thickness of flare is thin (0.05 [mm]), structural strength of the cicular model and the dodecagonal model are almost the same. However, when film thickness of the flare are thicker (0.15 [mm]), structural strength of the two models are clearly different as shown in Fig. 16. One of the reasons for this difference seems to be stress concentration at the inside of the dodecagon torus (Fig. 17); this stress concentration is not significant in the model with thin flare. Because of occurrence of stress concentration, the dodecagonal model tended to collapse and the structural strength of the dodecagonal model were lower.

As shown in Fig. 15 or Fig. 16, some results are deviated from the interpolated curves. The deviations may be attributable to the dependencies of the finite element mesh pattern to the collapse load. We found that the finite element model tends to kink along the mesh boundary. As a result, the finite element model as shown in Fig. 13 inherently excludes some possible buckling pattern, causing overestimation or underestimation of the buckling load.

Fig. 17. Stress contours map of the dodecagonal inflatable aeroshell.
3.3. Comparison between FEA results and experimentals

This subsection describes the comparison between FEA results and experimental results obtained from the low-speed wind tunnel tests in order to verify the order of the validation of the numerical models. Fig. 18 and 19 show the comparison between the numerical results and the experimental results for the inflatable aeroshell with circular torus and for that with dodecagon torus, correspondingly. The experimental results shown in the figures are those obtained from the low-wind tunnel tests carried out in 2012. As shown in the figures, the structural strength of the inflatable aeroshells calculated by FEA is larger than that obtained by the experiments. In addition, the differences between the two results are larger for the model #00 than that for the model #01. This may be attributable to the fact that the numerical model does not consider the initial out-of-plane deformations at all; the model #00 has larger amount of out-of-plane deformations than the model #01.

Fig. 18. Comparison between FEA results and experimental results for model #00 (with circular torus).

Fig. 19. Comparison between FEA results and experimental results for model #01 (with dodecagon torus).

4. Conclusions

Results of a series of low-speed wind tunnel tests are presented that were carried out for the purpose of investigating the structural strength of the proposed inflatable aeroshell. Through the results, we have found that the initial out-of-plane deformations and the torus scale rate $S$ of the inflatable aeroshell are primary factors that dominate the structural strength of the inflatable aeroshell. Numerical results for the inflatable aeroshell are also presented that are based on the nonlinear finite element method. There exists clear difference between the experimental and the numerical results, which may be attributable to the initial out-of-plane deformation of the inflatable aeroshell that are not considered in the numerical models. Future work will be accounting for this out-of-plane deformation in the FEA models for more precise prediction.

Acknowledgment

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Reference