EXPERIMENTAL STUDY OF BUCKLING PROPERTIES OF COMPOSITE LATTICE STRUCTURES FOR LAUNCHER APPLICATION

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Keywords: Composite, Lattice structure, Buckling, Launcher application

Abstract

Composite lattice structure is the structural concept which consists of helical and hoop ribs intersecting each other in a regular pattern. This concept seems very suitable for launcher structures because of its light-weight nature. But in order to apply this structure for launcher structures, it's so essential to understand the buckling properties under significant compressive load. In this study, experimental approach for evaluation of buckling properties for various composite lattice structures is described. We conducted the compressive tests to understand the buckling properties for cylindrical lattice shells with and without outer skin, and also conical shell.

1. Introduction

Weight reduction and cost reduction are the main issues to be improved for all the launcher structures. JAXA is now studying the system concept for the next flagship launcher [1] which will be alternative to the existing H-IIA and H-IIB, in which it is necessary to get international competitiveness of launch capability and cost. In structural technical field, increasing application of composite structures is considered to be the most promising approach to reduce the structural weight and cost.
Composite lattice structure is the structural concept which consists of helical and hoop ribs intersecting each other in a regular pattern. Under compressive and bending load, helical ribs are the main load carrying path using their unidirectional properties, and out-of-plane deformation of helical ribs are supported by hoop ribs by their unidirectional tensile properties, so it is very efficient structural concept for composite structure using under such loading conditions.

In our former study, the buckling properties for a simple cylindrical lattice shell without skin is investigated. [2] But considering various forms of launcher structure, it's also important to

figure out the buckling properties of various shapes of lattice structure other than simple cylindrical structure without skin.
The purpose of this study is to investigate the buckling properties for cylindrical lattice shells with and without outer skin, and for conical lattice shell, using the large-size manufacturing demonstrator. With experimental and analytical approach, to establish the design and manufacturing guideline is also the future goal of this study.

2. Design of demonstrators

2.1. Cylindrical shell demonstrators with and without outer skin

In order to understand the effect of outer skin for the buckling properties of composite lattice structures, we chose simple cylindrical shape for the demonstrator with diameter of 2.5 m. And we thought it's so important to figure out the skin effect clearly that we have outer skin on the upper half of the demonstrator, and no skin on the lower half of the demonstrator as shown in Figure 1.
For this design situation, we applied the numerical design procedure to decide the number of helical and hoop ribs, and the thickness and the width of the ribs to minimize the mass of cylindrical lattice shell, which was described in other studies [3].
For the preliminary design, three constraint equations were to be considered which described the critical global buckling force of the shell, the critical local buckling force of helical ribs, and the critical force due to the compressive strength of helical ribs. The considered objective function was the mass of the shell. Figure 2 shows the design parameters of the lattice ribs.

Regarding the outer skin, we predicted it has some effect of improving the buckling properties of lattice shell, by restricting the in-plane and out-of-plane deformation of the helical and hoop ribs. But on the other hand, skin thickness directly leads to the weight of the structure. If it has very thick outer skin, it would have very high buckling properties, but as a result of skin thickness it would be inappropriate design as an application for a launcher structure for its large structural weight.
So in this study, we set the purpose as evaluating how much the buckling properties would improve by having the outer skin which is as thin as possible.
In order to evaluate the roll of the skin, we supposed to allow the local buckling of the outer skin under lower compressive load and decide the thickness of skin as 0.25 mm by unidirectional hoop layer.
Finally, the values represented in Table 1 were set for the demonstrator.

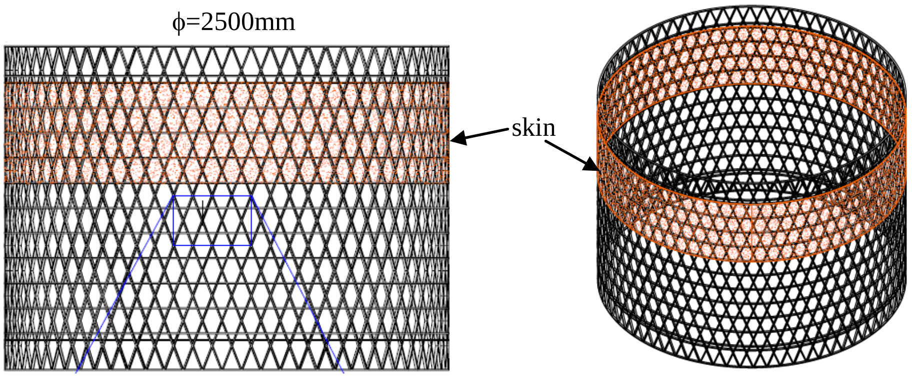

Figure 1. The outer view of cylindrical demonstrator with and without skin.

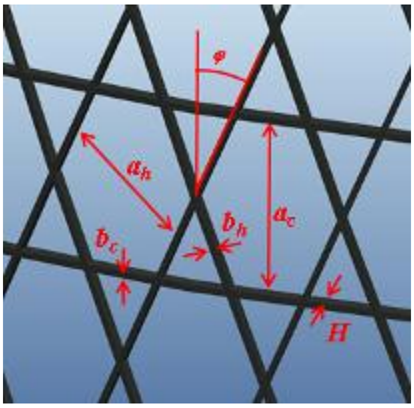

Figure 2. The definition of design parameters of the lattice ribs.

Radius	R	1250 mm
Height	L	1850 mm
Number of hoop ribs	N_c	15
Number of helical ribs	N_h	71
Helical rib angle	f	21.4 deg
Distance of hoop ribs	a_c	142.9 mm
Distance of helical ribs	a_h	103.2 mm
Width of hoop ribs	b_c	7.0 mm
Width of helical ribs	b_h	7.0 mm
Rib thickness	H	15.0 mm
Skin thickness	t_s	0.25 mm
Height of skin	L_s	578.4 mm

Table 1. The design variables set for the cylindrical demonstrator.

2.2. Conical shell demonstrator

The purpose of conical shell demonstrator is to evaluate the applicability of a composite lattice structure for a structure of a payload adapter. In case we take any structures for a payload adapter, it should be usually in a conical shape, because of the difference of the payload interface diameter from a launcher diameter. In this study, we decide the upper diameter as about 1200 mm, the lower diameter as about 2100 mm, and the height as about 450 mm. Figure 3 shows the overview of our conical demonstrator.

For this dimension, we applied the numerical design procedure to decide the number of helical and hoop ribs, and the thickness and the width of the ribs to minimize the mass of conical lattice shell, which was described in other studies [4].

Finally, the values represented in Table 2 were set for the demonstrator.

Upper diameter	d	1228 mm
Lower diameter	D	2140 mm
Height	H	450 mm
Number of hoop ribs	N_c	7
Number of helical ribs	N_h	50
Width of hoop ribs	b_c	6.5 mm
Width of helical ribs	b_h	6.5 mm
Rib thickness	H	12.0 mm

Table 2. The design variables set for the conical demonstrator.

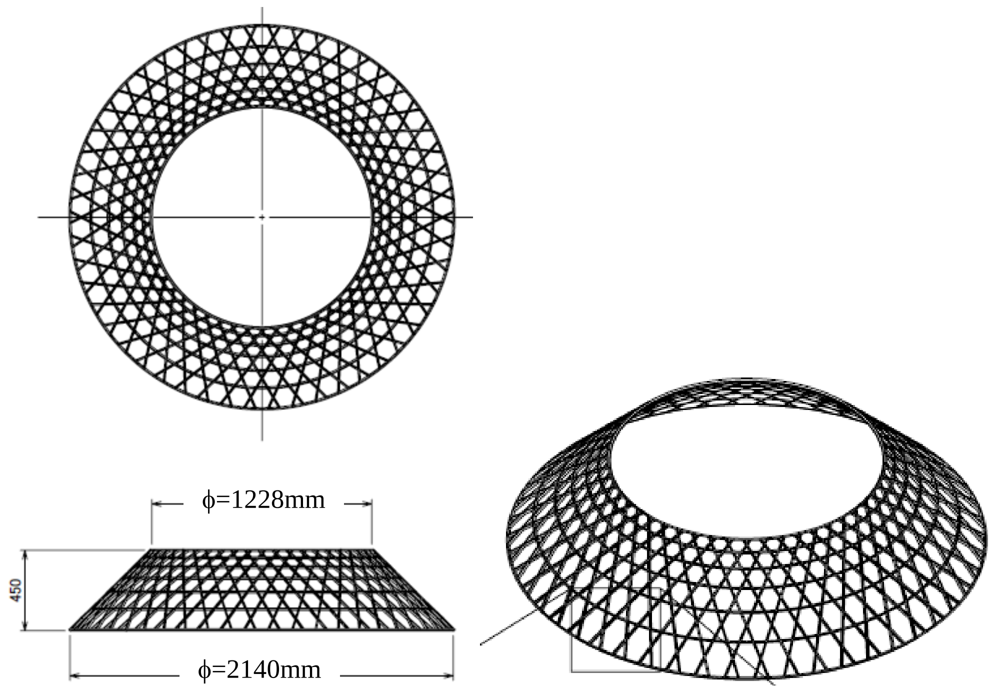

Figure 3. The outer view of conical demonstrator.

3. Manufacturing

We chose the wet winding process for the full scale demonstrator, which was considered to be the most well-balanced in the quality and manufacturing cost from our former test results.
The most important issue for manufacturing this structure is how to make a flat surface at the rib intersecting point without misalignment of the fibers. Fiber misalignment or buildup around the rib intersecting point is undesirable for the structure, because such phenomenon leads to significant loss of strength and stiffness. From this point of view, we used silicon rubber blocks as the expansion tooling, which provide lateral compaction of the ribs during cure. The image of the expansion tooling is shown in Fig. 4. As a result of some trial tests, we could prevent a buildup at the intersecting points.
The low-cost aspects of the manufacturing process developed in this study are shown below:

- The mandrel was built in a simple and low-cost design by steel frame and steel skin plate assembled by welding, shown in Figure 5.
- The mandrel was also used as the curing tool when heated from inside the mandrel, so that no autoclave or conventional oven were needed for curing process.
- Low-cost commercial-grade carbon fiber and matrix resin were used instead of conventional aerospace-grade, and also, no prepreg was used because of the wet winding process.
- The winding process was continuous and one-way in the semi-automatically controlled trajectory. In the winding process, carbon fiber tows were self-located in the grooves between silicon rubber blocks and kept in the accurate position restricted by the blocks, which lead to the efficiency of the process. The winding process is shown in Figure 6 and Figure 7.

Manufacturing result of the demonstrator is shown in Figure 8.

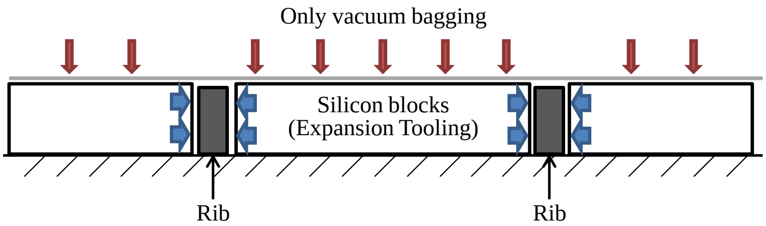

Figure 4. Image of the expansion tooling.

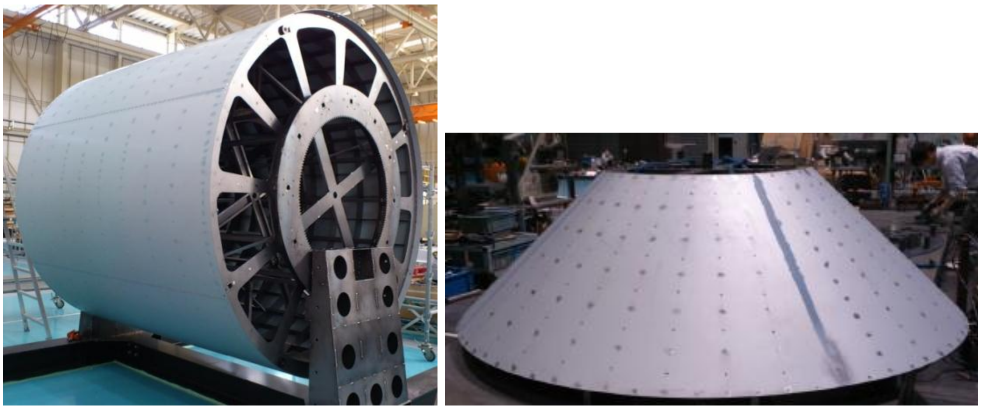

Figure 5. The low-cost mandrel for the demonstrator. (Left : Cylindrical, Right : Conical)

Figure 6. The winding process for cylindrical demonstrator and its skin.

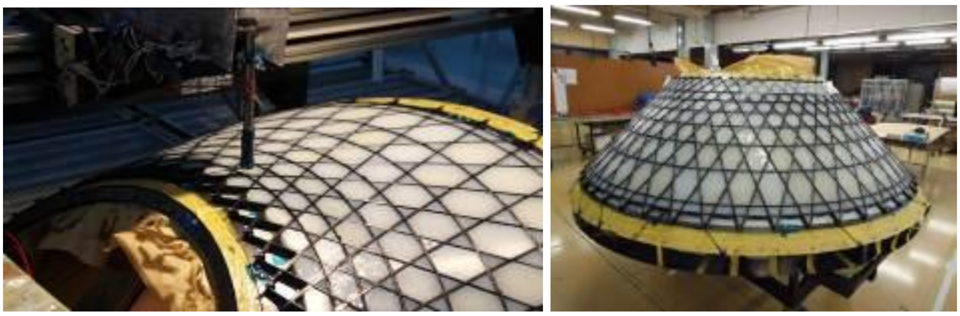

Figure 7. The winding process for conical demonstrator.

Figure 8. The manufacturing results of demonstrators. (Left : Cylindrical with skin, Right : Conical)

4. Experimental results

Full-scale compressive test for these demonstrators were conducted to check the global stiffness and buckling load. For the cylindrical demonstrator, we cut it apart for demonstrator without skin and with skin as shown in Figure 9.
The height of each cylindrical demonstrator is about 580 mm.
The test setup is shown in Figure 10 for conical demonstrator and in Figure 11 for cylindrical demonstrators with skin and without skin. We used the large-scale structural test facility of JAXA and axial compression was loaded with the speed of 0.5 mm/min.
In these tests, we measured about 170 points of rib strains, 20 points of displacements, and compressive force of load cell for each demonstrator.

The load-displacement curve measured in the test is shown in Figure 12. The global stiffness of the test was about 230 kN/mm for both cylindrical demonstrators with and without skin, while about 35 kN/mm for conical shell. So it was figured out that the presence of outer skin didn’t have the effect for improving the global stiffness of the lattice shell.

For the conical demonstrator, it fractured under the load of 450 kN. Before it fractured suddenly, the significant out-of-plane deformation of the shell was observed, and the helical ribs were loaded rather large bending moment. So it was figured out that the our-of-plane stiffness was important for this type of conical lattice shell to improve the global buckling properties.

On the other hand, regarding both cylindrical demonstrators with and without skin, they fractured under the load of 1200 kN. The local buckling of skin started at very early stage when the compressive load was very small, and after that, the compressive behavior was almost the same. All the fractured loads were lower than previously expected, but they should be investigated from the viewpoint of strain data of helical and hoop ribs and the distribution of the compressive load along the circumferences.
The typical strain data showed that the buckling started to occur just before the local fractures of ribs happened at rather narrow region of the circumference of the shell. So this was probably in conjunction with loading imperfections.

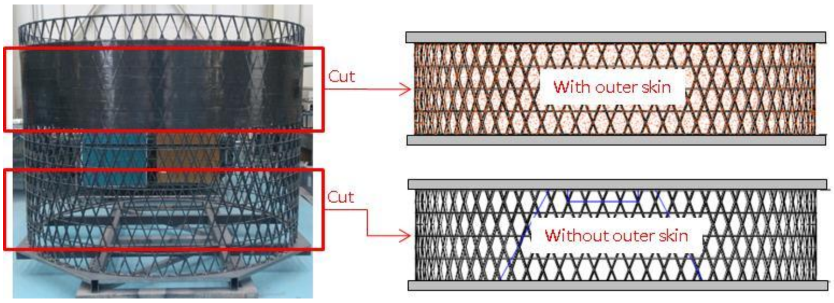

Figure 9. The test articles for cylindrical demonstrator with and without skin.

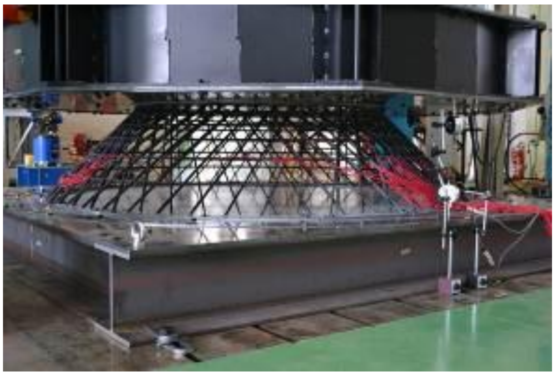

Figure 10. The test setup for conical demonstrator.

Figure 11. The test setups for cylindrical demonstrators with and without skin.

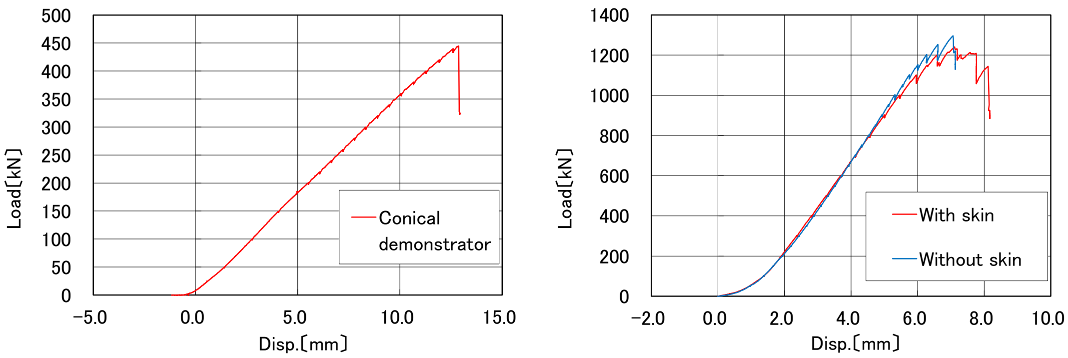

Figure 12. The load-displacement curves of the tests. (Left : Conical, Right : Cylindrical)

5. Conclusion

The possibility of applying low-cost composite lattice structures for launcher structure by cylindrical shape and conical shape, and with skin or without skin is shown in this study by manufacturing the large scale demonstrator and conducting full-scale tests.
The low-cost manufacturing process based on the wet winding method was developed, and it was proven that the process we set were suitable for this structure, and the mechanical properties were evaluated.
In the full-scale compressive test, we could evaluate the global stiffness and the buckling properties for these demonstrator, but further analysis and evaluation will be needed to understand more detail of the general characteristics.
We want to study the buckling properties with other dimensions of the rib cross-section, and establish the design guidelines for the various shapes of the composite lattice structure of launcher application in the future study.

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