Nonlinear Behavior of Stretchable Membrane and Its Application to Space Structure Systems

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We propose a more general concept of variable geometry structures than that of Variable Geometry Truss (VGT), which is frequently cited as a typical example of such variable adaptive structures. The new concepts and structure systems with flexile structural elements such as cables and membranes have various active elements other than simple truss members. They can provide specific mechanisms to control, and adapt themselves to various changes of their environments, purposes, and so on. Possible properties of stretchable membranes are described with some examples of available stretchable materials, since only utilizing stretchable membrane can realize the concept corresponding curved lines, surfaces, and volumes. Then we focus on a basic concept of general variable geometry structures with stretchable membrane elements including those inspired by morphological changes in nature. Some applications for space structure systems are also illustrated. Finally, mechanical properties and nonlinear behaviors of such membrane elements are summarized, and examples of numerical analysis for such elements are attempted.

I. Introduction

Flexible elements including cables and membranes are indispensable in the development of future space structure systems, since such elements allow the system to be lightweight and to obtain high package efficiency. However, there exist some problems to fully utilize these elements. One is that most flexible elements have no or less compressive resistance. This property causes nonlinear and often unpredictable behaviors of these elements. Such systems require specific mechanisms that can provide adaptive functions and motions controlling themselves and fitting themselves to various changes of their environments, purposes, and so on.

Variable geometry truss (VGT)[1,2] is frequently cited as a typical example of variable adaptive structures. It can alter its shape due to some active members. In this paper, we show a more general concept of variable geometry structures, which includes various active elements other than truss members. The concept reminds us adaptive structure systems in nature including living organisms. They use tensile materials, which reduce total weight[3], and various morphological changes in plants, insects, and animals are observed to adjust environmental or their own changes[4]. This paper focuses on a basic concept of variable geometry structures with stretchable membrane elements including those inspired by morphological changes in nature.

Meanwhile, stretchable properties have been considered as undesirable generally in engineering, because both geometrical and material nonlinearity must be treated. However, only stretchable membrane might be able to realize

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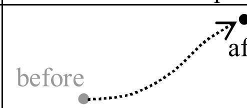
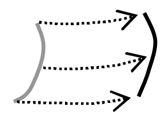
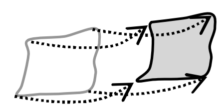
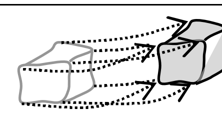
such variable geometry structures with curved lines, surfaces, and volumes. We also apply the concept into space structure systems. Finally, mechanical properties and nonlinear behaviors of such membrane elements are summarized.

II. Concept of Variable Geometry Structures

VGT is a representative variable geometry structure, which alters its own shape using active elements. In this case, an active element is a truss member expanding or contracting only in one dimension. Considering flexible structural elements such as cables and membranes, however, we can develop the concept more general one with multidimensional active elements. Table 1 shows the proposed classification of general variable geometry structures based on a dimension of an active element. VGT is categorized as a set of Variable Geometry Line (VGL)s, and its elements are rectilinear. The detail of the general concept of variable geometry structures is discussed in this chapter.

Table 1. Category of Variable Geometry Structures

	an active element defined by	graphic expression of basic concept
VGL: Variable Geometry Line including VGT (Variable Geometry Truss)	transition from a point to a point	 transition creates a variable line
VGS: Variable Geometry Surface	transition from a line to a line	 transition creates a variable surface
VGV: Variable Geometry Volume	transition from a surface to a surface	 transition creates variable volume
VGQ: Variable Geometry Quarteric Element	transition from a volume to a volume	 transition creates a variable quarteric element

A. Variable Geometry Line

An active element of VGL is defined by transition from a point to a point. Accordingly the active element makes variation of relative position between certain two points. Figure.1 is a specific case of a set of VGLs. Its active element, a truss member, usually expands or contract in one dimension. However, VGL is not specified in the case of such a linear active member. An active element of VGL is allowed to produce an arbitrary curved trajectory connecting two points.

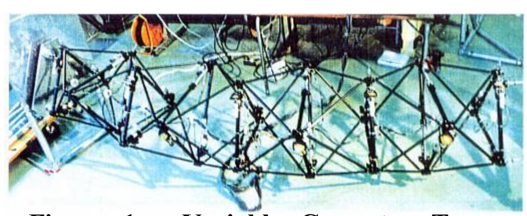
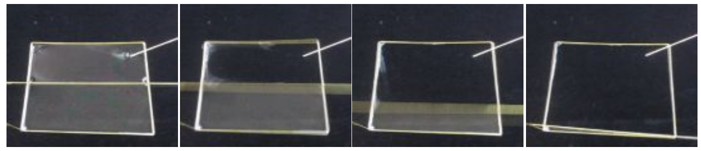


Figure 1. Variable Geometry Truss. *VGT is a typical but specific example of a set of VGLs.*

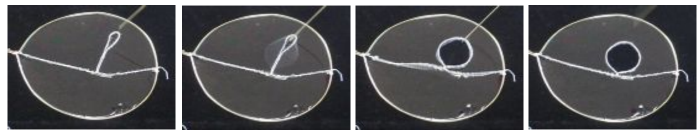
B. Variable Geometry Surface

An active element of VGS is defined by transition from a line to a line. Accordingly, the active element makes variation of relative position between certain two lines. VGS is not specified in the case of a planer active element. An active element of VGL is allowed to produce an arbitrary curved surface trajectory connecting two lines.

Figure 2 shows two examples of VGS activated by surface tension forces of soap film. In Fig.2 (a), soap film is divided into two by a brass tube at first. When one film is broken, a brass tube is moving by surface tension force of the other film. In the same way, a looped thread is spreading by surface tension force when the inner soap film is broken (Fig.2 (b)). These cases are both typical VGS, because both a straight line (a brass tube) and a curved line (a looped thread) are activated along line-to-line trajectories. The active motions change the relative position of a square/circle brass frame and a brass tube/a looped thread, respectively.



(a) Surface tension of soap film rolls a small brass tube.



(b) Surface tension of soap film strains a loop of thread.

Figure 2. Example of VGS (Variable Geometry Surface). *Surface tension of soap film changes relative relation of lines.*

C. Variable Geometry Volume

An active element of VGV is defined by transition from a surface to a surface. Accordingly, the active element makes variation of relative position between certain two surfaces. VGV is not specified in the case of a specific solid active member. An active element of VGV is allowed to produce an arbitrary curved volume trajectory connecting two surfaces.

Figure 3 shows an example of VGV in space structure systems: inflatable space antenna experiment. An inflatable structure is changing its forms due to inner pressure of working fluid. In this case, membrane surface is activated along a trajectory from an initial stowed position to an inflated position. The active motion changes the relative position between component membrane surfaces.

Figure 3. Example of VGV (Variable Geometry Volume). *In the case of inflatable structures, membrane surface is inflating due to inner pressure of working fluid. Relative position between membrane surfaces is changed.*

D. Variable Geometry Quarteric Element

An active element of VGQ is defined by transition from a volume to a volume. Accordingly, the active element makes variation of relative position between certain two volumes. VGQ is not specified in the case of such a hypercube active member. An active element of VGQ is allowed to produce an arbitrary curved trajectory connecting two volumes.

Figure 4 shows examples of variable geometry volumes in soap film structures. Figure 4 (a)-(c) demonstrate soap film put up within tetrahedral brass frame. According to growing air pressure, inner tetrahedral curved volume change to increase. An example case of hypercube is shown in Fig.4 (d). In the same way, inner cube change to its volume according to inner air pressure.

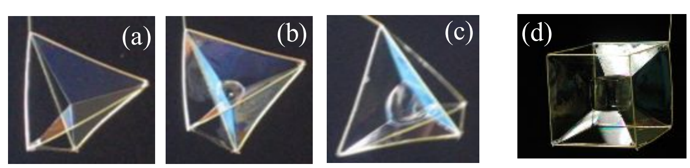


Figure 4. Example of VGQ(Variable Geometry Quarteric Element). *The form of soap film is decided by balance between surface tension, gravity force, and inner air pressure. A change of their balance deforms the relation of inner and outer volume.*

III. Variable Geometry Structures with Stretchable Membrane Elements

The following chapter describes variable geometry structures with stretchable membrane elements. At first we show well-functioning examples of stretchable membrane structures in nature. Microstructure observation of such stretchable membranes is demonstrated to clarify the mechanism of their stretchable properties. And we consider artificial variable geometry structures, which can be realized only after introducing stretchable membrane elements. Application of stretchable membrane elements for space systems is also discussed.

A. Stretchable Membrane Structures in Nature

Various morphological changes in nature have been observed to give a clue for new membrane structures[4]. Among them coleopteran and bats are noted that such flying organisms can store their membrane wings compactly and frequently. The former can fold and store hind wings under rigid forewings, and the latter can fold their membrane wings between their arms and fingers shown in Fig.5. We focus on membrane wings of bats because of their high package efficiency.

Membrane wings of bats are so stretchable and flexible that they can quickly follow a large movement of their arms and fingers. Also they can be folded compactly after a flight. This feature is seen from Microchiropteran (wingspan: approx. 10cm) to Megachiroptera (wingspan: approx. 2m). Details of membrane wings are shown in Fig.6. Hybrid structure with elastic fibers network and finely-wrinkled skin provide stretchable and flexible properties. Adding to movements of arms and fingers, muscular tissues directly activate membrane wings locally.

Figure 5. Horseshoe Bats. *Membrane wings seem to follow the movements of arms and fingers without remarkable wrinkle or folds.*

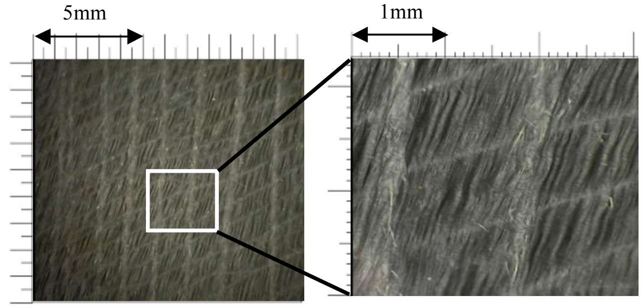


Figure 6. Details of Wing Membrane of Bats. *Elastic fibers network and finely wrinkled skin provide stretchable and flexible properties.*

B. Variable Geometry Structures with Stretchable Membranes

Stretch property of membrane is generally regarded as undesirable for current artificial membrane structures on ground and on orbit. Because analysis of stretchable membrane has both material and geometric nonlinearity, and static and dynamic behaviors of them are sometimes not predictable. It is part of the reason that commercially available stretch fabric such as clothing items and bandage do not require excessive stretch property. Therefore, using stretchable membrane has not been addressed previously.

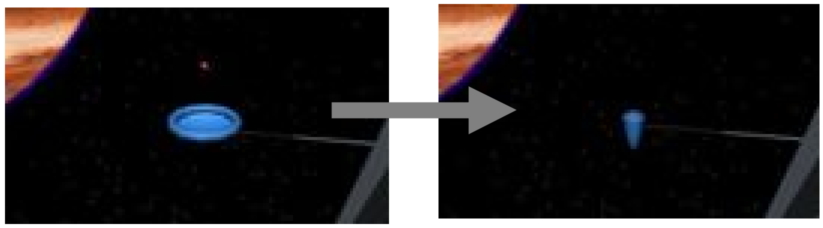
Meanwhile, only stretchable materials might be able to realize generalized variable geometry structures, because they include curved lines, surfaces, and volumes mentioned in the previous chapter. Moreover, the following engineering merits of using stretchable membrane are considered in reference to the observation of bats wings.

1) Stretchable membrane can follow dynamic and rapid movements of supporting rigid frames.
2) Stretch property can assist to be stored, and to reduce slack or wrinkle regions.
3) Stretchable membrane might realize structures which repeat deploy and store motion.
4) Stretchable membrane is not sensitive against environmental disturbance because of its nonlinearity.

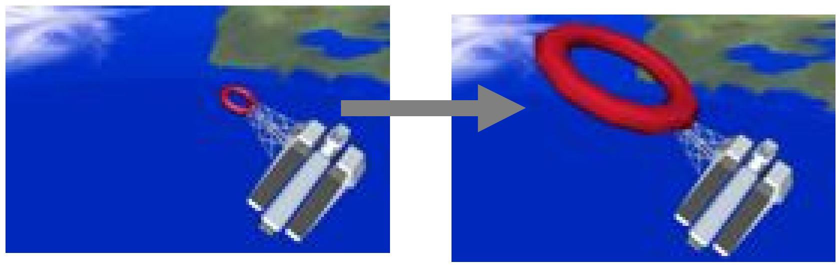
C. Application of Stretchable Membrane Elements for Space Systems

From the viewpoint of the above merits, we propose the following applications of the new deployable structures or adaptive structures based on variable geometry structures with stretchable elements for space systems.

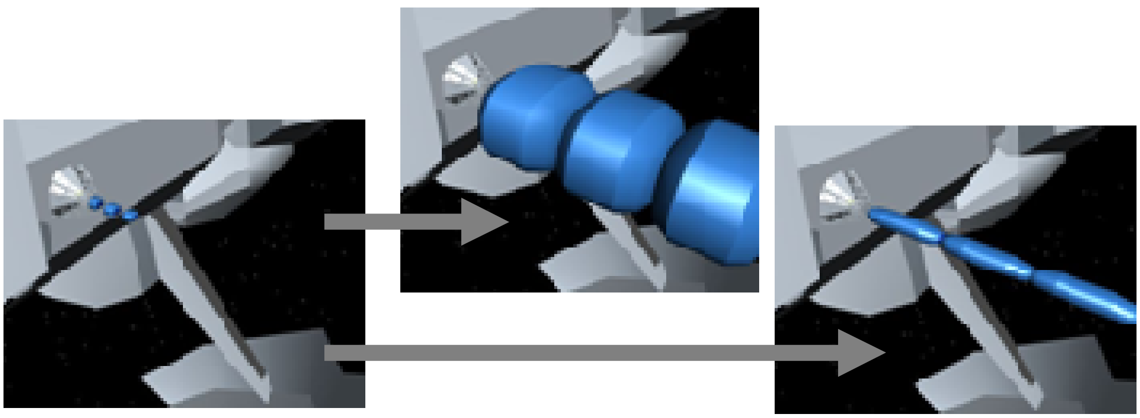
1) Debris catcher to enshroud floating debris at a slow speed (Fig.7a).
2) Sun shield which is repeatedly deployed and stored.
3) Container which can vary its shape and capacity fitted to the content.
4) Various curved surfaces with seamless membrane (Fig.7b).
5) Inflatable structures, of which the inflating direction reflects anisotropy of stretchable membrane (Fig.7c).



a) capture system for slowly floating debris

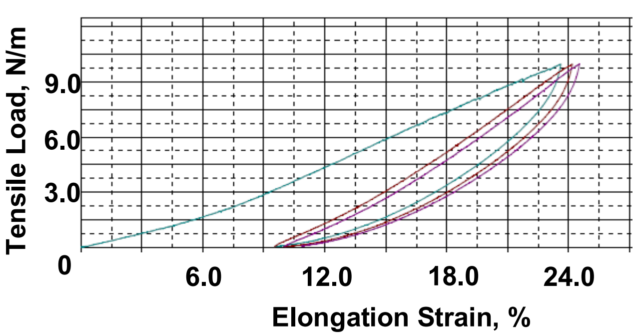


b) curved surface with seamless membrane

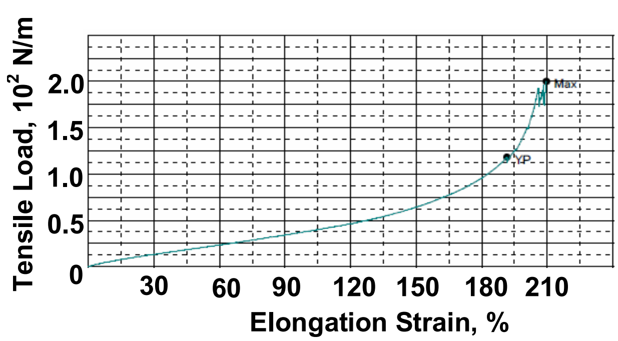


c) inflating direction reflecting anisotropy

Figure 7. Examples of Space Application of Stretchable Membrane Elements. *Case a is VGS (Variable Geometry Surface) and the other cases are VGV (Variable Geometry Volume).*



(a) Load-strain curve of metal mesh



(b) Load-strain curve of elastic bandage

Figure 8. Load-Strain Curve of Stretchable Membranes. *Stretchable membranes, has very small Young's modulus, high breaking extension, and nonlinearity including hysteresis.*

IV. Basic Mechanical Properties of Stretchable Membranes

However we have showed variable geometry structures with stretchable membrane elements, what is a "stretchable" membrane? This section focuses on mechanical properties of such elements including qualitative evaluation of stretchable properties.

A. Qualitative Evaluation of "Stretchable" Properties

In this article, we mention how to evaluate "stretchable" property in this study. Figure 8 illustrates load-strain curves of specimens of "stretchable" membranes. One is metal (Au-Mo) mesh, and the other is elastic bandage. We conducted tensile test on them. Shown in these curves, hysteresis is observed in the cycle test of the metal mesh, and very large deformation over 200% is recognized in break test of the elastic bandage. From these results, to define stretchable material is summarized as the follows.

1) A "stretchable" material has low Young's modulus.

2) Breaking strain of a "stretchable" material is rather large.

B. Available Stretchable Membrane Materials

Various "stretchable" membranes are marketed for medical use, apparel fabric, and so on. Generally, there seems to be three types of them classified by dominant determiner of stretchable property. In the first type (Fig.9 Type A), stretchable property is due to component's high elasticity, which means a basic component itself is stretchable. This type includes rubber or elastomer sheets. In the second type (Fig.9 Type C), stretchable property is due to mesoscopic structures such as weaves, finely-wrinkle, and lattice with non-stretchable components. This type includes string bags and some plastic nets. In the third type (Fig.9 Type B), stretchable property is due to hybrid effects of the former two types. This type includes mesh stockings, elastic bandages, hide, and leather. Membrane wings of bats are in this type.

C. Numerical Analysis Examples of Stretchable Membrane Element

How to analyze static and dynamic behavior of stretchable membrane elements is generally difficult, because both geometrical and material nonlinearity are not negligible. However there exist many approaches of nonlinear finite element analysis, we attempt to analyze two cases of stretchable elements. One is uniform rubber sheet with large deformation, and the other is plastic lattice net with large shear deformation. As mention in the previous article, stretch property of the former material is due to the nature of silicon rubber, and that of the latter material is due to mechanism of lattice structure with non stretchable components.

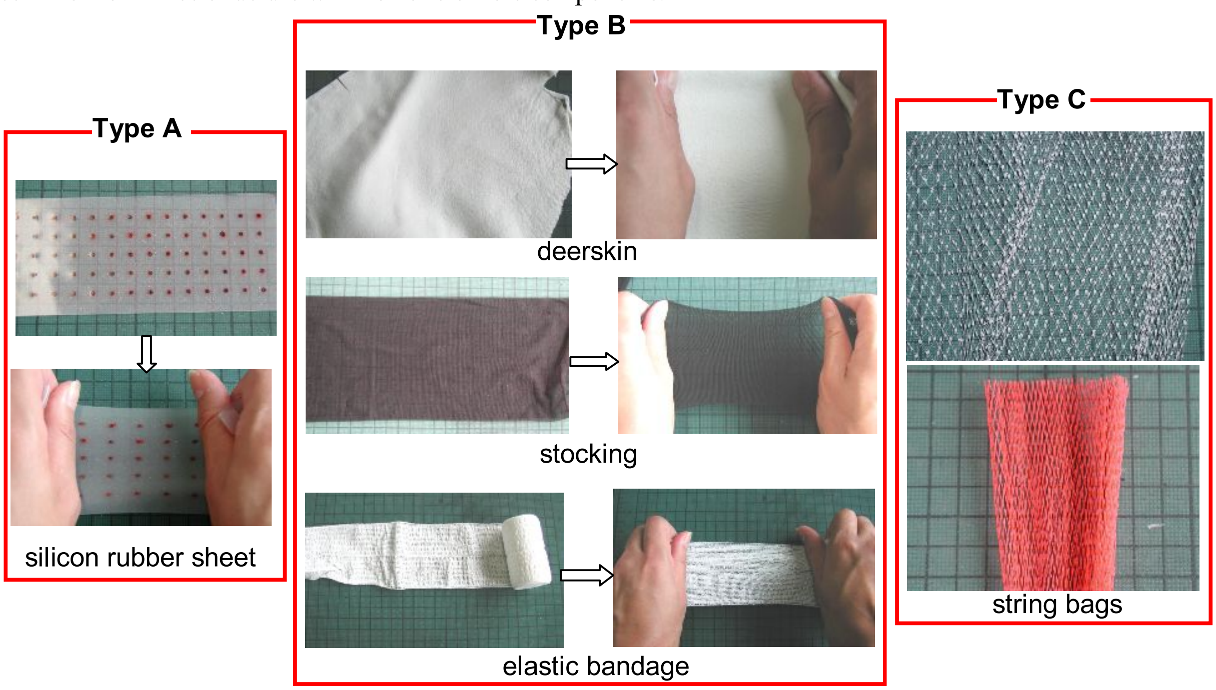
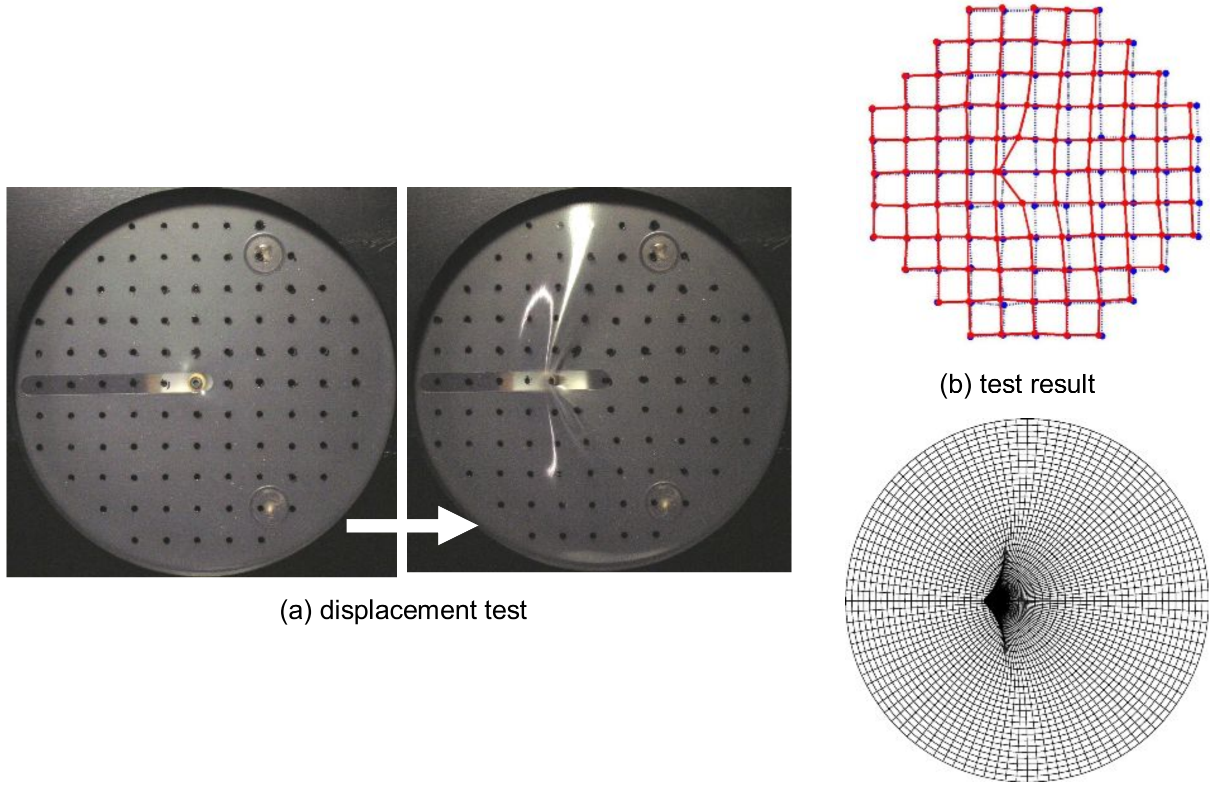


Figure 9. Available Stretchable Membranes. *They can be classified by dominant determiner of stretchable property.*



(a) displacement test

(b) test result

(c) analysis result

Figure 10. Displacement test and analysis of silicon rubber sheet. *We attempt to analyze displacements of silicon rubber sheet based on tension field theory.*

For simplicity, in the case of silicon rubber sheet, deformations produced by displacement of a center node are analyzed using FEM based on tension field theory. In the case, we carried out corresponding displacement tests shown in Fig.10 (a). A boundary of circular silicon rubber sheet (0.3mm in thickness and 150mm in diameter) is fixed by a circler ring. And displacements of marked grid points are read out from the picture before/after a center grid point is forcibly moved. In Fig.10, the results before and after deformation are indicated in blue and red, respectively.

Moreover in the case of a lattice net, we attempt to analyze 2-dimensional deformation produced by shear displacements of faced sides using nonlinear FEM. One cell of the lattice net is 5.0mm square, diameter of a lattice frame is 0.1mm, and Young's modulus of the frame is 300kg/mm^2. A result example is shown in Fig.11. Color indicates shear stress of elements.

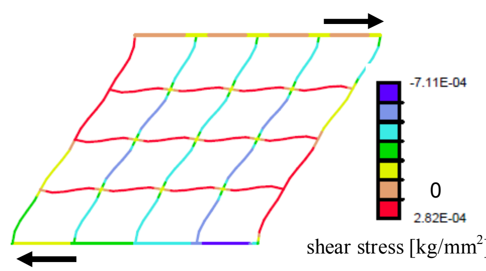


Figure 11. Example of 2D analysis on net structure. *We attempt to analyze shear deformation of planer net structure based on nonlinear FEM.*

V. Conclusion

How to fully utilize flexible elements including cables and membranes is the key technology of the development of future space structure systems. This paper introduced one approach of it: positively utilizing stretchable materials. "Stretchable" property is defined by small Young's modulus and large breaking strain. And the property leads various useful applications for space structure systems. And only stretchable materials can realize general variable geometry structures, which components include curved lines, surfaces, and volumes.

Acknowledgments

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References

[1]Miura, K., Furuya, H., and Suzuki, K., "Variable Geometry Truss and Its Application to Deployable Truss and Space Crane Arm," *Acta Astronautica*, Vol. 12, No. 7/8, 1985, pp. 599-607.

[2]Natori, M.C., and Iwasaki, K., and Kuwano, F., "Adaptive Planer Truss Structures and Their Vibration Characteristics," 28th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Material Conference, AIAA-87-0743, 1987, pp.143-151.

[3]Wainwright, S.A., Biggs, W.D., Currey, J.D., and Gosline, J.M., *Mechanical Design in Organisms*, Princeton University Press, Princeton, 1982.

[4]Kishimoto, N., Natori, M. C., Higuchi, K., and Ukegawa, K, "New Deployable Membrane Structure Models Inspired by Morphological Changes in Nature," 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA-2006-1898, 2006.