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Tensegrity Structures Apply to Spacecraft Structures: The State of the Art and Future Perspectives

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Abstract **-** The research on tensegrity has not stopped since its birth. But there are few practical applications due to the special shape of tensegrity structures. Some advantages of tensegrity structures closely match the spacecraft structures requirements, however, less practical applications are applied to spacecraft structures than architecture. This paper summarizes the advantages of tensegrity structures to lightweight and simple, have the ability of adjustable pre-stress and deformation. Meanwhile, high load-bearing while lightweight, withstand harsh working conditions (temperature, vibrations, impact), high reliability and special function have been sorted out as the requirements of spacecraft structures. After analysis and comparison, conclude that the adjustable pre-stress and deformation ability of tensegrity structures will be the key research direction. Also maximize the use of material characteristics to make different parts of the tensegrity structures may greatly improve the utilization rate of tensegrity structures.

Keywords**:** Tensegrity, Tensegrity Characteristic, Spacecraft Structures Requirements, Advantages of Tensegrity Structures.

1. Introduction

Tensegrity refers to the integrity of a stable structure which is integrated by discontinuous structural members (usually bars or struts, which is compressed) and continuous structural members (usually cables or tendons, which is pre-stressed tensioned). Moreover, the cables are flexible and global components, while the bars are stiff and local components [1]. So far, there is no strict definition of tensegrity structures, but the tensegrity structures have the characteristics of tensegrity and have been applied to architecture, art and mechanical engineering. However, there are few spacecraft consist of tensegrity structures. This paper presents the characteristics of tensegrity structures and how to meet the requirements of spacecraft structures. At first, describes the characteristics and application of tensegrity structures. Then, introduce the requirements of spacecraft structures from the aspects of purpose, process and efficiency. Whether the characteristics of tensegrity structures are match the requirements of spacecraft structures are reported next. Finally, conclusions and future perspectives are discussed and provides a research direction for the application of the tensegrity structures on the spacecraft structures.

2. Tensegrity

The term tensegrity was created by Richard Buckminster Fuller as a contraction of ‘tensional’ and ‘integrity’ [2]. Figure 1 shows the simple three-dimensional tensegrity structures.

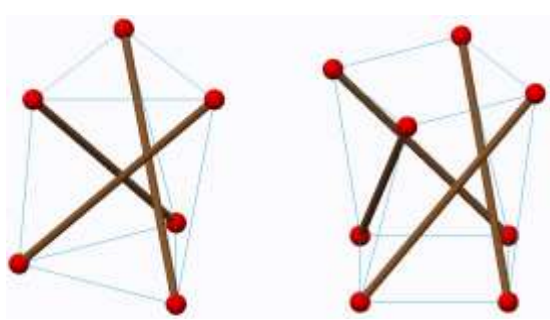

Fig. 1: The simple three-dimensional tensegrity structures. Left: 3-bar. Right: 4-bar.

There are six characteristics of a tensegrity structure [1][3]: a) The structure is free-standing, without any support; b) The structural members are straight; c) There are only two different types of structural members: struts carrying compression and cables carrying tension; d) The struts do not contact with each other at their ends; e) The structure is self-stress; f) The structure is deformable.

In real life, the above characteristics are mainly applied to architecture and robotics.

The tensegrity structures in architecture are simple and maybe the optimal structural systems. Because it only includes two types of structural members and have minimum possible number of structural members to maintains its stability, while each member is straight and carry only axial force. Moreover, tensegrity structures have many advantages when they are used as long-span structures to cover a large space without columns inside [1]. Tensegrity structures are more efficient and lightweight than conventional structures in reduce the buckling failure by adjust the structural stiffness. Furthermore, the joint of structural members can be the same in order to save the cost.

In the field of robotics, tensegrity structures are utilized as ‘smart’ structures [4][5] and deployable structures [6][7]. The shape of tensegrity structures can be adjusted to meet different requirements in different circumstances. The change of shape will break the self-equilibrated of tensegrity structure, so the whole tensegrity structure can move or deploy. The way of adjusted the shape is adjusting the pre-stresses or member lengths, which the responses are predictable [7]. Moreover, the control systems (sensors and actuators) can be easily embedded and implemented in the straight (one-dimensional) members.

To summarize, the most advantages of tensegrity structures are lightweight and simple, have the ability of adjustable pre-stress and deformation.

3. The requirements of spacecraft structures

Spacecraft is a vehicle or machine designed to fly in outer space. There are many types of spacecraft, but every spacecraft has the similar experience when travel to outer space. That suggests the structures of spacecraft have the similar requirements, including high load-bearing while lightweight, withstand harsh working conditions (temperature, vibrations, impact), high reliability and special function.

3.1. High load-bearing while lightweight

The structures of spacecraft are designed for support, connect and protect the payload other than itself. Usually, the engineer will make the full use of the material and structural forms, to the purpose of gain high load-bearing spacecraft structures, make sure the structures will not lose stability or crush while in the process of transport, launch and work. Furthermore, if the spacecraft structures are high load-bearing while lightweight means high efficient. The lightweight requirement originates from the desire to minimize the launch costs and possibly maximum the payload on a single launch vehicle [8]. The utilize of lightweight composite materials, advanced manufacturing techniques and lightweight based design can minimize mass and maximize structural stiffness.

3.2. Withstand harsh working conditions

Between production and completion of the final mission, the spacecraft will experience some peculiar stages, include ground transportation, launch acceleration and entry into space. In those stages, the spacecraft will face extreme temperature changes, intense vibration and impact during separation. To achieve the support, connection and protection purpose, the structures of the spacecraft are required to withstand high-low temperature alternating, resonance and significant impact by absorb or relieve these harmful energies without lose stability or crack.

3.3. High reliability

All spacecraft except single-stage-to-orbit vehicles cannot get into space on their own, and require a launch vehicle (carrier rocket). As the final stage, failure or damage of any part of the spacecraft will lead to extremely serious accidents. All the previous processes are serve for spacecraft, meanwhile, the replacement or maintenance is inconvenience when the spacecraft is working, so the whole spacecraft (include structure) must require high reliability.

3.4. Special functions

Generally speaking, the structures of energy system, detection system and motion system have its own special needs. For example, solar panels and antennas need to be folded in launch progress while unfolded in working progress, nozzle need to be multi-degree of freedom attitude adjustment in zero gravity environment, shape need to be change while back to earth or landing (walking on) other planet, etc. The special functions of spacecraft structures are determined by the mission of spacecraft.

4. The tensegrity characteristics analyse according to spacecraft structures requirement

The advantages and disadvantages of tensegrity will be present in this part from the aspect of spacecraft structures requirement.

4.1. Load-bearing

In this part, suppose a load bearing only tensegrity structure which is a fixed structure of the spacecraft, such as a landing leg, support frame, etc. This tensegrity structure is assumed to be prismatic structure of dihedral symmetry [1]. Figure 1 shows the three-bar and four-bar Prismatic structure of dihedral symmetry. Stability was not considered in the analysis. For comparison, suppose a homogeneous structure. Each cross-sectional area perpendicular to the load is A. The height of whole homogeneous structure is H. The load is F. Consider a n-bar tensegrity structure with the same volume(weight), height and load. Suppose the cables are rigid body and no weight. The Angle between the force (along the direction of bar) and the load is α. The length of the bar is L. Suppose the resultant force cause by cable on a joint is f. Cross-sectional area of each bar is A_b, the force along the direction of bar is F_b. The stress in the homogeneous structure is indicated by σ_1 while the stress in the tensegrity structure is indicated by σ_2. Figure 2 shows the supposed homogeneous structure and tensegrity structure (n=4). The relation between σ_1 and σ_2 shown in Eqs. (1) - (2).

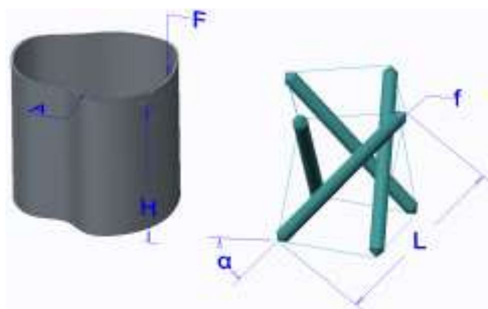

Fig. 2: The supposed homogeneous structure and tensegrity structure (n=4).

$$L = \frac{H}{\cos\alpha} \tag{1}$$

$$\sigma_2 = \frac{F_b}{A_b} = \frac{\frac{F}{n\cdot\cos\alpha} + f}{\frac{A\cdot H}{n\cdot L}} = \frac{F}{A\cdot\cos^2\alpha} + \frac{f\cdot n}{A\cdot\cos\alpha} > \sigma_1 = \frac{F}{A} \tag{2}$$

That means a n-bar tensegrity structure is more likely crush than a homogeneous structure. So far, there is no tensegrity product as a load bearing only structure in real life.

4.2. Working conditions

The tensegrity structures show some advantages in harsh working conditions such as intense vibration and significant impact. First, during the period of launch and flight, the tensegrity structures can avoid resonance. Every part of spacecraft has its own natural frequencies. Tensegrity structures can change its natural frequencies by adjust the length of bar or change the pre-stress level [9], which is convenience to deal with resonance and improve safety. Second, during the period of separate and landing, the tensegrity structures can avoid significant impact forces due to their natural compliance and structural force distribution properties [10]. The shape of tensegrity structures can restore to its original state after impact. Moreover, adjust the connectivity, geometry or pre-stress of tensegrity can change the stiffness of whole structure [11] which is an important property to deal with significant impact problem.

However, the high-low temperature alternating problem is mainly solved by the characteristics of the structural materials themselves, the tensegrity structures are no better than others in the same composition material. On the contrary, temperature has a significant influence on pre-stresses of cable, while the change of pre-stresses of cable will affect the whole shape of tensegrity structure. There are no tensegrity structures specifically designed to deal with high-low temperatures alternating till now.

4.3. Reliability and functions

Reliability and functions of tensegrity structures are closely related to each other. There is no advantage in using a tensegrity structure as a single function structure, since there is a principle for enhancing system reliability: to keep the system as simple as is compatible with the performance requirements [12]. However, the tensegrity structures are more reliable if they are multifunctional. Because the members of tensegrity can be divided into bar and cable. The tensegrity structures obtain different characteristics by increase the quantity of each member and it is easy to replace or fix the member when it is out of order. Taking advantage of adjustable pre-stress and deformation, a tensegrity structure can be used as both a buffer structure and a walking mechanism [10], and as a vibration absorber and a deployable mechanism [6,7]. Therefore, the characteristics of the tensegrity structures have certain advantages in dealing with the high reliability and special functions required by the spacecraft structures. At present, most of the applications and researches are in the deformation of tensegrity structures.

5. Conclusion

It can be seen from the above that the advantages of deformation and adjustable pre-stress in tensegrity structures are useful when apply to the structures of the spacecraft, while the others are not. This determines the research direction of application of tensegrity structures on spacecraft. For example, the advantages of lightweight and long-span in architecture are not reflected in the spacecraft structures, but the ability of adjustable pre-stress and deformation can solve the problem of vibration and impact. Currently, the tensegrity structures have been practical applied to the deployable structures and space robots. In the future, use the high compressive strength material for bar and high tensile strength material (carbon fibre) for cable may greatly improve the utilization rate of tensegrity structures. In that case, the development of tensegrity structures apply to the spacecraft structures will be promoted.

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