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Abstract

Tensegrity is the word coined by Buckminster Fuller as a contraction of tensional integrity. A tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space. Tensegrity structures are mechanically stable not because of the strength of individual members but because of the way the entire structure distributes and balances mechanical loads. Tensile forces naturally transmit themselves over the shortest distance between two points, so the members of a tensegrity system are precisely positioned to best withstand stress. Thus, tensegrity systems offer a maximum amount of strength for a given amount of material. Man-made structures have traditionally been designed to avoid developing large tensile stresses. In contrast, nature always uses a balance of tension and compression. Tensegrity principles apply at essentially every size-scale in the human body. Macroscopically, the bones that constitute our skeleton are pulled up against the force of gravity and stabilized in a vertical form by the pull of tensile muscles, tendons and ligaments. Microscopically, a tensegrity structure has been proposed for the skeleton of cells. This report contains the results of a feasibility study and literature survey to explore the potential of applying tensegrity principles in designing materials with desired functionalities. The goal is to assess if further study of the principles of tensegrity may be exploited as an avenue for producing new materials that have intrinsic capabilities for adapting to changing loads (self-healing), as with the ongoing reconstruction of living bone under loading. This study contains a collection of literature that has been categorized into the areas of structures, mathematics, mechanics, and, biology. The topics addressed in each area are discussed. Ultimately, we conclude that because tensegrity is fundamentally a description of structure, it may prove useful for describing existing materials, but does not provide guidance in the development of new materials because it does not address the issue of how such structures form.

Keywords: tensegrity, self-assembly, cellular mechanics.

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Contents

1 Introduction

Figure 1: *Needle Tower* by Snelson (1968)

Tensegrity systems are self-stressed structures relying on a discontinuous distribution of compression members combined with a continuous network of tension members that define a volume in space [2]. The origin of tensegrity structures can be traced to an equilibrium structure by the sculptor Johansen from a 1921 exhibition in Moscow. The structure resulted from research completed by the Russian constructivists and was reported in the book by *Von Materiel zu Architektur* by L.M. Nagy, first published in 1929. The word tensegrity was coined by Buckminster Fuller many years later as a contraction of *tensional integrity*. Fuller was exposed to the idea by his student, the artist Snelson, who in the autumn of 1948 created a sculpture with an innovative structural design that did not appear to have any weight-bearing element, but was nonetheless stable. Fuller's immediate fascination with the questions of stability and how tensegrity systems can be systematically described, or classified, have become topics of ongoing research in a number of subject areas.

Tensegrity structures are mechanically stable not because of the strength of individual members but because of the way the entire structure distributes and balances mechanical loads. The tension-bearing members in these systems map out the shortest paths between adjacent members. Tensile forces naturally transmit themselves over the shortest distance between two points, so the members of a tensegrity system are precisely positioned to best withstand stress. For this reason, tensegrity systems offer a maximum amount of strength for a given amount of material.

Our interest in the concepts of tensegrity stems from its potential explanation for linking structure, sensing, and response in biological systems, an idea pioneered at the cellular level by Ingber [1]. It is this close connection between structure and function that gives biological systems their inherent resistance to degradation, the ability monitor their condition, the ability to respond intelligently to avoid or mitigate failure, and the means for rapid repair in the event of damage. These characteristics are desirable in engineering materials as well. The recognition that nature has devised effective solutions to many problems has given rise to the field of biomimetics. In the materials regime, silk and nacre are frequently cited as model materials. Synthetic versions of these materials have been made, but their properties are inferior to the examples produced by nature. Our hypothesis is that greater success in developing biologically-inspired materials could be achieved if our understanding extended beyond composition and microstructure to include function, sensing, and response. The scope of this challenge is very broad and with any technical difficulties. Our investigation of tensegrity is intended to broaden our current way of thinking.

In this report, we present a literature survey on tensegrity. The body of literature we collected can be grouped into four subject areas:

(1) Structures

(2) Mathematics

(3) Mechanics

(4) Biology

For each area, we discuss the topics that have been investigates and provide a list of representative citations.

2 Literature survey

The order in which subject areas are presented is selected to begin with structures, where the concepts of tensegrity first appeared, and end with biology, where tensegrity has been used to form the basis of a theory describing cell structure and the connection between structure and function. The intervening sections on mathematics and mechanics describe the analysis that ultimately allowed this structural concept to be applied to biological systems.

2.1 Structures

The unique properties of tensegrity structures make them excellent candidates for many structural applications. Conveniently, specific advantages and disadvantages have been collected by Hanaor [5]. The advantages include geometric variety and intricacy, light and intriguing appearance, absence of massive anchorage systems, simple connections, high structural redundancy, low tolerance sensitivity, and convenient deployability. The disadvantages include geometric and conceptual complexity, flexbility and large deflections, potential for long buckling-prone bars, and our relative lack of experience with structures of this type. Nonetheless, there have been many applications in architecture. Tensegrity offers architecture good covering for large open spaces, temporary structures such as exhibition halls and crisis response hospitals, as well as dramatic visual effects in more traditional buildings. Ideas of tensegrity naturally lead to the design of deployable structures [3], which have seen many space applications.

The literature in this area includes many examples that cover the basic concepts of design and application using both linear [9] and nonlinear [7] analysis. Tensegrity structures can take a variety of forms, including domes [4, 6], tension structures like cable nets and pre-stressed membranes [2], general cable-strut systems [10], and spline beam and grid cell structures [1]. There has also been investigation of tensegrity principals in application to smart structures which combine sensing, actuating, and load carrying functions [8].

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2.2 Mathematics

Tensegrity structures are composed only of simple tension and compression members. This simplicity leads very naturally to mathematical description. Independent of the construction method, structures with tensegrity architecture are modeled mathematically as a collection of points that satisfy simple length constraints. Tension members keep points together and compression members keep points apart. A specific tensegrity, based on the truncated icosahedron, is the geometrical form used to model the carbon molecule C_{60}, also known as buckminsterfullerene or "buckyball". The mathematics used to study this structure is representative of the mathematics involved in the study of more general tensegrity structures, as expressed by Chung and Sternberg:

> Several areas of mathematics can be brought to bear on the analysis of C_{60}. Geometry, naturally, describes the shape of the molecule; it is a shape that was known to the Renaissance geometers... Topology is the appropriate tool for exploring an entire family of fullerene molecules related to C_{60} topological arguments show which fullerene molecules might exist and which are impossible. The branch of mathematics called group theory is the most central to an understanding of the buckyball; group theory describes the symmetries of the molecule and thereby determines some of its most distinctive properties... Finally, the area of discrete mathematics called graph theory helps to explain the remarkable chemical stability. [1]

Mathematical analysis has been used to study the relationship between structure and stability [3], including formal analysis rigidity and flexibility [5]. Group theory has been applied to describe symmetries in tensegrity structures, to classify them, and to develop systematic algorithms for constructing structures with increasing complexity [2]. Aside from the chemical aspects quoted above, graph theory has been used to develop methods for finding the minimal additions needed by a structure to make it a stable tensegrity [4].

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2.3 Mechanics

Many interesting mechanics problems arise in analysis and design of tensegrity structures. Nonlinear computational methods are required because the geometrically deformable structures are capable of large deflections [1]. As a result, the analysis is considerably more complex than that of stiff, geometrically rigid structures such as trusses. Indeed, the earliest mechanics work aimed to explain why tensegrity structures are stable even through they appear to have too few members, as dictated by the design rules for trusses [2]. Many analytical and numerical techniques are used to solve these problems including; dynamic relaxation, modal analysis [10, 7, 8, 13], linear and nonlinear dynamics [9], and Lagrangian formulations in continuum mechanics [5, 6]. The process of analyzing tensegrity structures can be described in three phases [4]: (1) form finding to determine the configuration in the absence of self-stress, (2) determining the configuration after application of self-stress, and finally (3) determining the configuration after application of external loads.

Tensegrity structures containing members with nonlinear material properties have been studied [11, 3]. Analysis of damping and vibration properties reveals the structures as a whole display less damping than the natural damping present in structural elements themselves [12]. There have been studies on reconfiguration of tensegrity structures, with application to packing or for deployable structures. Conversely, one can analyze the potential for reconfiguration of the internal geometry or mechanical characteristics subject to the constraint that certain external dimensions do not change [14].

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2.4 Biology

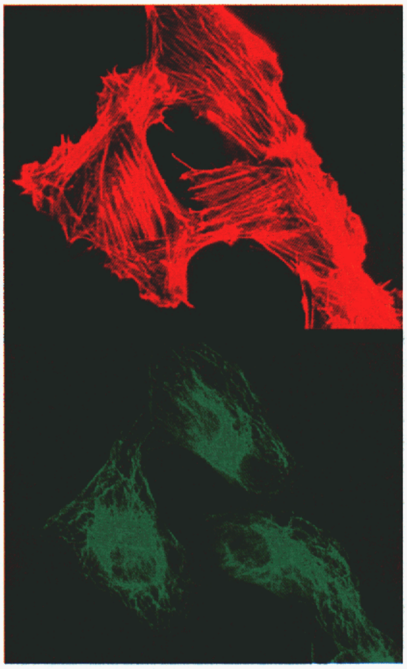

Figure 2: Microfilaments (red) and microtubules (green)

Many researchers in the fields of cell biology and biomechanics have become interested in the concepts of tensegrity. For example, a models explaining deformability of adherent cells has been proposed using tensegrity architecture. The idea of describing the cytoskeleton (CSK) as a tensegrity structure was pioneered by Ingber [1]. In this model, a tension-compression network provides the shape stability of the entire cell. The CSK is organized as a network of tension bearing elements (actin filaments) and isolated compression-bearing elements (microtubules). Even today, Continuum approaches to modeling the structural properties of cells typically assume an elastic cortical shell surrounding a viscoelastic core [2]. These continuum models fail to reproduce experimental findings that can be explained assuming a tensegrity structure. The most significant among these is the linear stiffening of cells under load, which has been reproduced by several cell models based on tensegrity [8, 10, 7]. In attempting to predict the mechanical properties of cells, comparison of tensegrity models with more simple open-cell foam models or prestressed cable nets show the combination of tensile and compressive members is needed to reproduce observed behavior of wide range of deformations [6]. There is experimental evidence showing the mechanical response of cells when the compression-bearing microtubules are disrupted is consistent with a tensegrity model of the CSK structure [9], both in terms of the measured drop in pre-stress and stiffness.

Ingber also proposed the idea that the tensegrity structure of cells is a significant component of how mechanical signals result in a chemical response [4] through the action of stretch-sensitive ion channels and signaling molecules. Furthermore, the combination of short compressive members combined with extended tensile members provides the mechanism in which local signals can be transformed to global response. A number of experiments have shown that cell shape plays a role in cell function [1, 5]. Stretched cells are more likely to divide, confined cells are more likely to die, and cells under intermediate conditions begin to differentiate themselves in tissue-specific manners.

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3 Conclusions

The basic mechanics of tensegrity structures can be described with relatively straightforward analysis due to the simple nature of their components, pure tension and compression members. Connection conditions between the components may become more complicated, including pinned connections, sliding connections, and rigid connections; however, none of these concepts are new to mechanics. As a result, one finds many commonalities in the literature across all the subject areas described in Section 2. The basic mechanics are simple to describe but the resulting deformation and reconfiguration of tensegrity structures under loads can be extremely complicated. For this reason, it proves to be a concept that can be applied in many areas, especially those in which structure, sensing, and response are tightly linked.

Fundamentally, tensegrity is a description of structure, features of which can be seen at many scales in nature. Certainly, there does seem to be a tendency for natural systems to be organized into structures balancing tensile and compressive members, from the structure of single cells to the muscles and bones of complete animals. However, as a description of structure it is less useful for providing the basis for the development of new materials. Ultimately, materials must be manufactured or grown, and for this aspect of material development, tensegrity does not provide any direct guidance. Namely, the driving forces that form these structures or cause them to self-assemble are not described by the concept of tensegrity. This shortcoming is evident in the modeling examples in the literature. None of the examples contained large numbers of members, or those that contained more than a few were constructed from regular repeating units. In part, this is due to the fact that the basic structural concepts can be explained with basic models. However, the difficulty of constructing the large scale, irregularly-structured tensegrities seen in nature is also a reason one does not find them in the modeling literature. One could certainly develop algorithms for generating these structures. With them, simulations could be used to reveal more complex phenomena, such as redundancy, collective behavior of members, and load redistribution due to local failures. However, one would still find it difficult to apply the results to the development of new materials without the means for manufacturing them.

We conclude that an engineering sciences-based study for the development of bio-inspired materials must begin with a basic understanding of how these materials form. *Self-assembly*, *growth* and *remodelling* are distinct processes contributing to the development of biological material. Growth, or conversely resorption, involves the addition or loss of mass. At a microscopic scale, it takes place as molecules self-assemble into larger units. The availability of molecules for self-assembly at a given site is determined by mass transport and chemical reactions. Remodelling results from a change in microstructure. These aspects must be understood in actual biotissue before they can be applied to the design and construction of bio-inspired materials. Modeling the properties and evolution of these materials requires the formulation of balance laws and the development of mathematical and computational models that can describe growth and remodelling, as observed in biological materials, at the continuum scale. The ability to model and simulate these processes will be indispensable if bio-mimetic and bio-inspired materials are to be realized. As a result, we have proposed to study self-assembly, growth and remodelling of biological material in an LDRD project beginning FY04 that will develop methods of modeling and simulation from continuum to molecular scales with validation provided by tissue culture and characterization.

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