Carbon Nanotube Fiber-Based Tensegrity Structures

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ABSTRACT

Tensegrity structures characterized by self-equilibrium and super-stability are space structures, which due to their properties are of interest to architects and civil engineers. This paper reviews the possible usage of carbon nanotube (CNT) fibers as the main cables in the design of tensegrity structures. The main aim of this research is to ascertain new ways of building extremely lightweight, durable, and customizable tensegrity wall systems. CNT fibers are a very promising candidate for the building material for such structures, due to their high mechanical strength, lightweightedness, corrosion and oxidation resistance, and the possibility to act as an artificial muscle. Researches show that implementing CNT fibers as the main cables of tensegrity structures provides advancement of lightweightedness, structural strength, and multi-functionality via customization of the structure. It was found that CNT fiber-based tensegrity wall structures could be useful in applications to real-world designs of novel engineering objects; specifically, objects in which lightweightedness, corrosion resistance, flexibility, high mechanical strength and customization are the key factors. These objects might eventually be deployed for a wide spectrum of situations, from post-disaster shelters or objects located in harsh climatic conditions to perhaps even extraterrestrial habitats.

Keywords: carbon nanotubes, flexible systems, tensegrity structures

1 INTRODUCTION

The rapid development of materials science, mainly nanomaterials, suggests that in the near future, such materials will be used in building architectural and civil enginering structures. Carbon nanotubes (CNTs) are one of interesting type of nanomaterials, which is used to produce CNT-based macroscopic materials including fibers [1]. CNT fibers are characterized by a high modulus 250 ± 60 GPa, high tensile strength of 2.4 ± 0.1 GPa [2], and the possibility to act as an artificial muscle [3]. All those aspects make CNT fibers a promising candidate, which can be used for the construction of new forms of spatial structures. The concept of building structures in which compression and tension forces are in balance was presented by Karl Ioganson in 1921 [4]. It was not until the work of K. Snelson in 1948 that tensegrity structures gained wider interest [5]. The term tensegrity is a portmanteau of “tensional integrity” coined by R. Buckminster Fuller in the 1960s [6]. Although 70 years have passed since the first presentation of Snelson's sculptures, tensegrity structures have found their use mainly as objects of art. However, more and more practical solutions are being proposed which employ tensegrity solutions, such as: the roof of the multi-purpose arena complex The Spodek in Katowice, Poland [7], Kurilpa Bridge in Brisbane, Australia [8], satellite antennas [9], and NASA's Super Ball Bot [10]. The timelessness of this type of construction solution allows us to assume that in the coming years, along with developments in materials science, we will be increasingly meeting tensegrity systems in new engineering design. This paper will present a tensegrity structure design for the construction of a lightweight, portable, and configurable covering using the latest achievements in the field of CNT fiber production. This covering will be mainly made out of carbon. Stretched elements – cables – are made of CNT fibers, and the compression element – struts – are made out of carbon fibers. Thus, usage of CNT fibers and the possibility of using them as artificial muscles [11] will allow changes in the form of the structure over time. Using CNT fibers and carbon fibers in the construction of tensegrity structures creates the possibility of building very strong yet very lightweight spatial structures. Such structures can be used in the construction of novel objects. Just like each era received its name from the main building material used at the time, through the wide use of nanomaterials in architecture and civil enginering, we should show that we currently live in the nanomaterials era. [12]

2 METHODOLOGY

The concept of a carbon nanotube fiber–based tensegrity structure is aimed at the design and construction of tensegrity structural systems, using carbon fibers and CNT fibers as the main materials. In the process of analyzing various tensegirty systems, a tri-directional tensegrity grid was selected. The next stage was to design and 3D model a virtual model. The model was created in the *Autodesk Fusion 360* software. Tensegrity structures are constructed through the usage of two main structural elements, struts and cables. In this project scenario, struts, which are compressed elements, were simulated as a carbon fiber reinforced epoxy. The material of tension elements – cables – were simulated as CNT fiber wires. The created model and applied materials where used for static stress simulation. In the preparation phase there is a physical model of the designed structural system using the proposed materials.

3 NUMERICAL SIMULATION

3.1 Geometry model

After analyzing the tensegrity constraints, the described structure was designed as a three-way grid [13]. The virtual model was created. The whole structure consists of three compressed elements and a continuous cable grid. The cables connect the individual nodes on the grid of an equilateral triangle. The distance between individual nodes is 22.2 mm. Compressed elements were designed as even-sided triangular pyramids with a length of individual edges equal to 31.4 mm. The angle between the base plane and the edge of the compression element is 45 degrees. The number of nodes on the upper surface is 34, the same number of nodes as on the bottom surface. The weight of the structure is 2.8 grams.

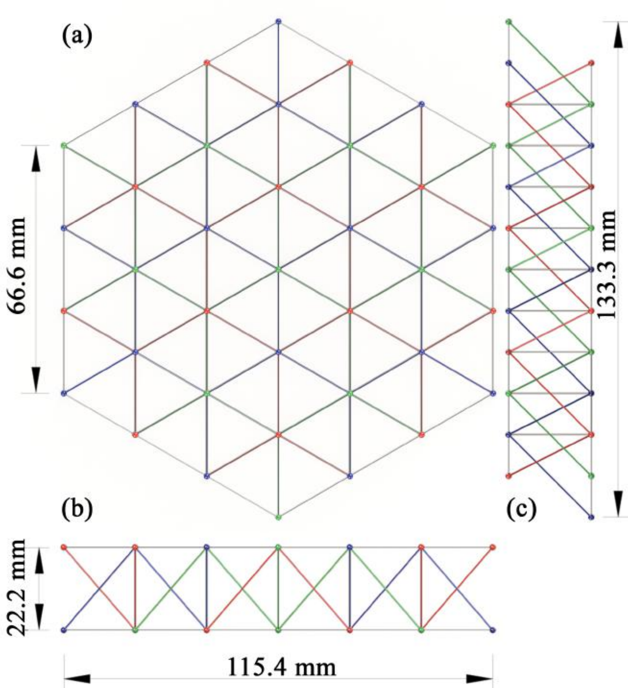

Figure 1: (a) Top view. (b) Front view. (c) Side view

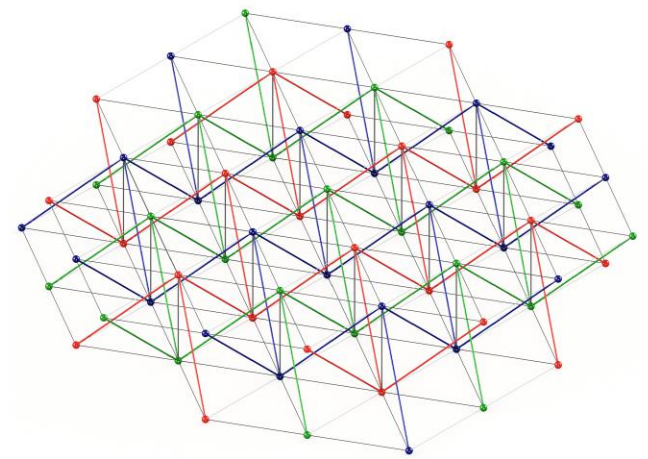

Figure 2: Ortographic view of proposed structure

3.2 Materials

For the construction of the structure, two materials were selected: carbon fiber reinforced epoxy for struts and CNT fiber wire for cables. The cross section of surface area of the strut is 0.79 mm^2. Material data from the Autodesk Material Library: Young's Modulus – 133 GPa, Shear Modulus – 53000 MPa, Yield Strength – 300 MPa, Tensile Strength – 577 MPa. The cable cross section surface area is 0.16 mm^2 and their parameters: Young's Modulus – 20 GPa; Shear Modulus – 14.40 MPa; Yield Strength – 2400 MPa; Tensile Strengt – 2400 MPa [2]. These data were used to simulate static stress in the designed structure.

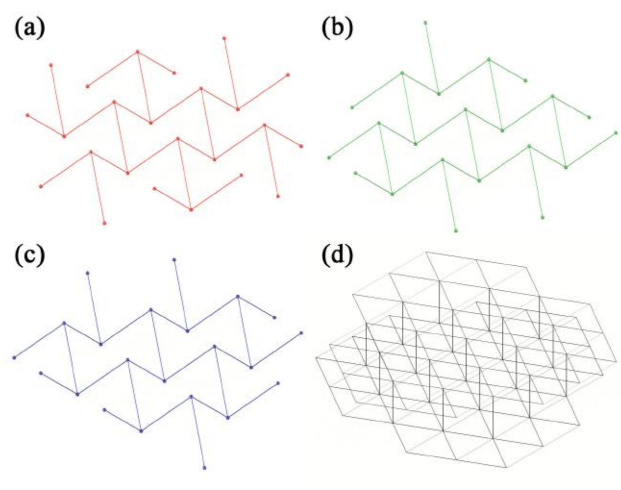

Figure 3: (a) First compressed component. (b) Second compressed component. (c) Third compressed component. (d) Continuum of tensioned components.

3.3 Simulation

Simulations were done to calculate the static stress using selected materials. The simulation was carried out in the *Autodesk Fusion 360* simulation environment. In the simulation, the model was subjected to a vertical force of 19000 N. The force was applied to 19 nodes of 1000 N each. Structural constraint was set to be fixed for all thirty four bottom nodes. The model passed the simulations successfully. The actual minimum safety factor was 3.28. Maximum structure displacement reached value of 11.31 µm. The conducted simulation presents very robust mechanical properties of the proposed usage of carbon fiber materials in tensegrity structures.

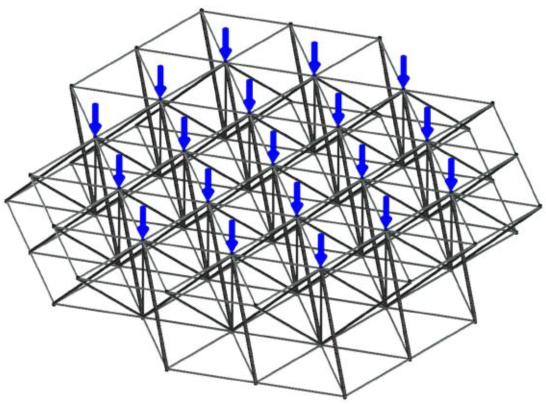

Figure 4: Load distribution – 1000N force applied for each node.

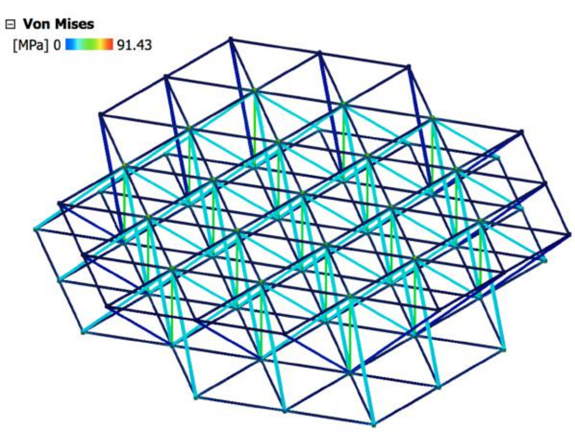

Figure 5: Stress simulation result – Von Mies.

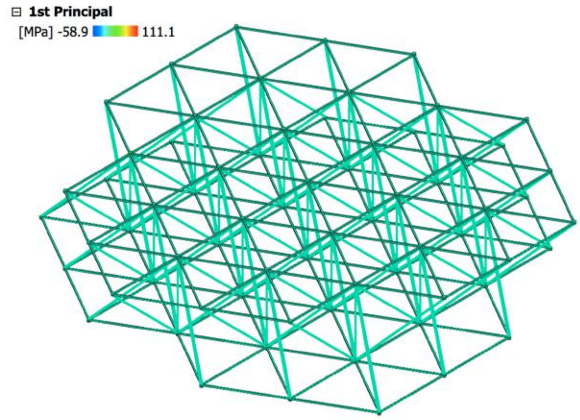

Figure 6: Stress simulation result – 1st Principal.

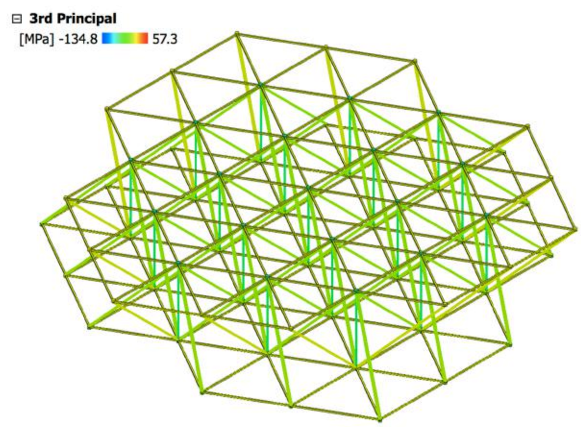

Figure 7: Stress simulation result – 3rd Principal.

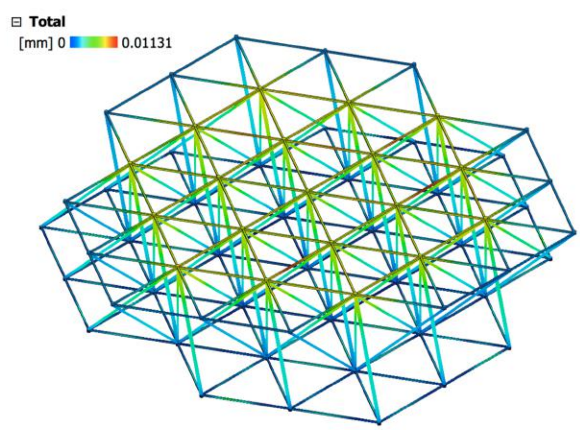

Figure 8: Structural displacement result under simulated load

4 APPLICATION

The preliminary studies on the potential usage of high strength carbon fibers and CNT fibers in the construction process of the tensegrity structure show the potential for application of this type of construction system in real life scenarios. The tensegrity system based on carbon fibers and CNT fibers simultaneously has a low weight and high strength. These properties show considerable potential for using such structures in novel engineering solutions. The spectrum of possible applications ranges from ultra light aircraft components to satellites, lightweight roofing, mobile shelters, and modular building construction elements. Along with technology and automation development, further applications of carbon nanotube-based tensegrity structures would find a place.

5 CONCLUSION

The concept of tensegrity stuctures has been around for the last century. However, until today, the wider applications of this system have not been discovered. The latest outcomes of production techniques of high-strength carbon nanotube fibers and carbon fiber composites opens up new possibilities for the application of this material in the process of tensegrity structural erection. Moreover, research on the possible usage of CNTs as artificial muscles would allow the construction of a structure that may, depending on demand, change form and function. The research presented in this article has a conceptual character and is in the initial stage of development. Further research is needed in the matter of future implementation of CNT fibers in spatial structures such as tensegrity.

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