

The Classification and Design of New Tensegrity Structure Based on the Area Coverage Concept*



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Abstract

This research was conducted to explore, classify and propose design principles for new types of tensegrity structures for area cover applications. Tensegrity structures are widely used in the fields of engineering and architecture to create bridges, domes, and buildings because the structures are flexible, lightweight and can be expanded into a variety of forms. Moreover, the tensegrity structure had a series of continuous cables in tension and another set of discontinuous struts in compression. It was usually flexible, lightweight, and capable of spanning wide ranges but considered complex and challenging to assemble. This practical research involves the classification, development of models, and their application to specific types of work. The research process is divided into six main steps: Classification, Summary, Hypotheses, Experiments, Results, and Deliveries. Experiments with physical models are also conducted to explore potential variations in tensegrity structures. This method helps verify forces, identify form-finding factors, and create efficient designs.

The results of this research can be used to guide the development of architecture, product design, and other designs by leveraging the classifications, principles, and methods established in this study. In addition, the research and experimentation process involve an in-depth exploration of the structural forms and properties of each type, leading to the creation of new designs and the ability to apply each structure according to its intended use. The development of such structures introduces numerous possibilities for comprehending Tensegrity structures and acts as a catalyst for advancements across various applications. The primary focus is on investigating the origins and historical evolution of Tensegrity structures, highlighting their advantages and disadvantages. Additionally, the research aims to classify existing types and propose a new Tensegrity structure with controllable width and length expansion. The overarching goal is to provide a comprehensive understanding, facilitate practical applications, and extend the design capabilities of Tensegrity structures.

Keywords: Tensegrity; Structure; Form-Finding; Lightweight

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Introduction

The tensegrity concept was the brainchild of two men, a professor, and a student. The first, Richard Buckminster Fuller, was appointed professor at Black Mountain College (North Carolina), United States of America) and also doubled as an architect, engineer, mathematician, cosmologist, poet, and inventor. The professor coined the term “tensegrity” from the words “tension” and “integrity” in 1955 (Fuller, 1982; Jáuregui, 2020). The second, Kenneth D. Snelson, was an accomplished sculptor and the first to model the original small tensegrity sculpture using the plywood X-piece, as presented in Figure 1. The individual has also showed a profound and intrinsic role in the development of tensegrity sculpture to the present day. The sculpture was presented to Buckminster Fuller for evaluation and found to be a solution that had been sought for years. Fuller had made exhaustive efforts to explore tensegrity concept, including terminology and the evolution of geometry using multidimensional vector systems and 3D, but challenges in combining the elements into a tangible model. It was discovered that Kenneth D. Snelson approved a detailed method to serve as a fundamental process for synthesizing science and art. Meanwhile, Buckminster Fuller pursued an alternative method by studying several potential geometric systems, particularly those focused on spherical shapes. These investigations were translated into models and empirical experiments to produce the primary methodological tool. The concept of Kenneth D. Snelson was explored for its potential application in architecture and engineering. The inquiries into the origins of tensegrity also sparked reflections about its inventor, an essential question for both Buckminster Fuller and Kenneth D. Snelson. However, prioritizing the exploration of fundamental principles and structural merits was considered more valuable than summarizing past arguments.

The basic structural members of tensegrity were found to include compression and tensile elements allowing the formation and maintenance of a firm shape. Tensegrity structures comprise a unique design concept characterized by a combination of discontinuous compression elements (struts) within a continuous tensile network (cables or tendons) (Fraddosio, Pavone, and Piccioni, 2019). The process ensures the parts receiving compression are not next to or touching each other. Kenneth D. Snelson had experience with compression and tension elements as indicated in Figures 1 and 2 and several other relevant works. This model was considered a simple straight pipe connection and referred to as Tensegrity Linear Systems.



Figure 1: Third Proto Tensegrity Sculpture, the "X-piece" Tensegrity Model
Source: Snelson (1948)

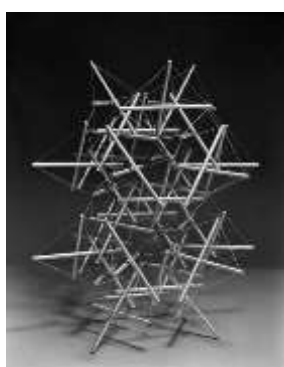


Figure 2: Tensegrity Sculpture
Source: Snelson (1948)



Figure 3: Geodesic Tensegrity Dome
Source: Fuller (1953) Photo by Gengnagel.



Figure 4: the Montreal Biosphere
Source: Fuller (1967). Photo by Cédric Thévenet.



The definition, advantages, and disadvantages of tensegrity structure were also explored. The concept was defined as the structural principle developed based on only two forces, compressive and tensile force, allowing an entire structure to join, form, and stabilize independently. The networked tensile forces generate internal compression within the transmissive structure while the compressive parts are not allowed to be connected or touched. According to (Motto, 2003), tensegrity system is in a stable self-equilibrated state and consists of a discontinuous set of compressed components inside a continuum of tensioned elements. The concept has also been defined by several scholars and observed to have a string (in tension) and bars (in compression) (Skelton et al., 2001). Another essential step identified in tensegrity structure was the determination of the geometric profile and the initial compressive force through the concept of form-finding (Xu, and Luo, 2010). The previous research by (Koohestani, 2012) also showed that tensegrity structure was pin-jointed, mechanically stable, and pre-stressed frameworks. (Ma, Chen, and Skelton, 2020) proposed minimal mass cantilever structures subject to yield and buckling constraints for the design of the simplest cantilever structure by tensegrity structure.

Objectives of the Research

1. To investigate the origin, history, and progress of tensegrity structure.
2. To classify the type of tensegrity structure.
3. To construct a new type of tensegrity structure.

Research Methodology

This research was conducted practically by combining primary methods with the objective. Furthermore, it aimed to develop a tensegrity structure for further architectural applications as a wide-span building to cover an area with different shapes. This was necessary because the initial design had some limitations, such as the complicated installation method which led to less popularity despite the potential as one of the most efficient structures. The six major stages used include classification, conclusion data, hypothesis, experiment, result, and delivery as presented in the following figure.

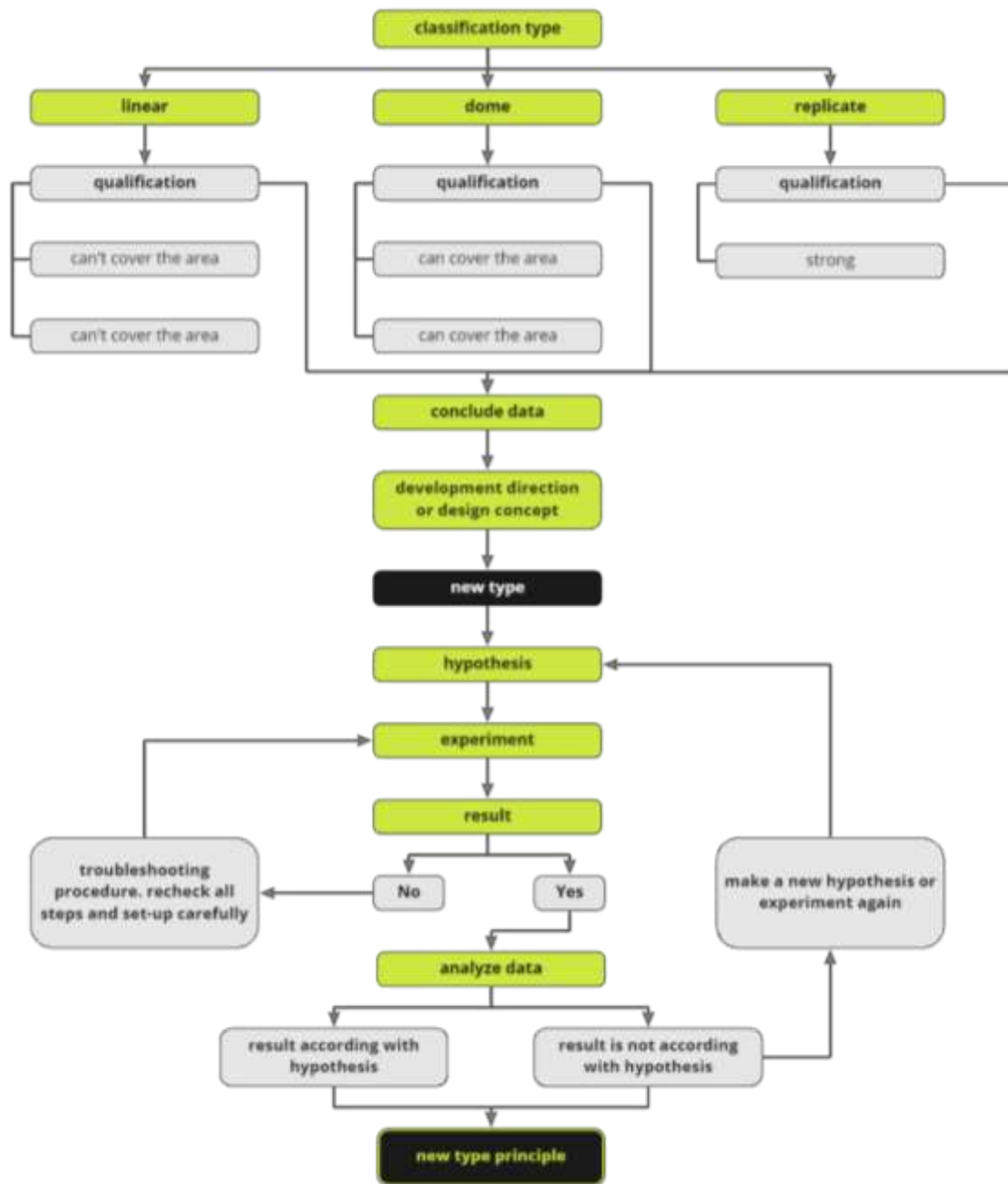


Figure 5: Design Research Process

Source: Authors

The first step was to categorize tensegrity structure due to the need to describe, define, and classify the concept for further development. There was also the need to ensure a more controversial and consistent classification. Therefore, this research attempted to present an opinion-based categorization with a focus on the expansion direction from the shape and form and to analyze each system's ability to allow modification. The second step focused on using the data from the classification by considering the original requirements of the systems to find the gaps or directions in the design to provide a new type of tensegrity structure with the ability to respond to comprehensive architectural applications. The third step was to formulate



the hypothesis that “what direction or design concept is expected in the new tensegrity structure?” The data from the classification made in the first step were analyzed to speculate on the feasibility of the experimental design. The fourth step was applied to conduct experiments on the physical and behavioral effects of the structure through modeling. The fifth step focused on result evaluation to ensure the objectives were achieved and the discovery of any goal not fulfilled would lead to the thorough examination of the methods applied for errors, followed by the conduct of another trial. The sixth step was used to analyze the data obtained from the results evaluated to ensure the hypothesis set was matched. The discovery of any mismatch would lead to the reevaluation of the concepts, methods, and results.

The well-designed process was required for effective research due to its ability to monitor and assist during the experiments. The process was initiated with the gathering of information for classification followed by the examination and exploration of the properties of each type in order to develop a new design.

Research Results

The 1st objective is to investigate the origin, history, and progress of tensegrity structure. From the research results, it was found that the results provided more clarity on the two individuals, Buckminster Fuller and Kenneth D. Snelson. These individuals were reported to be instrumental in developing the concept and demonstrating its working principles and potential. In conclusion, the inquiry into the origin of Tensegrity sparked contemplation regarding its inventor, a question of significance for both Buckminster Fuller and Kenneth D. Snelson. Nonetheless, prioritizing the exploration of the underlying principles held greater value than past arguments' conclusions.

The 2nd objective is to classify the classification of Tensegrity structures. In this research, Tensegrity is classified based on its properties and ability to change the direction of the shape of the structure and the area covered as if it were a surface structure. From the research result, it was found that It is classified as follows: 1. tensegrity Dome Structure, 2. Linear System Tensegrity Structure, and 3. Self-Repetitive Tensegrity Structure.

1) Tensegrity Dome Structure

Tensegrity Dome Structure was characterized by the ability to expand into a spherical shape covering an area without altering its form. The sub-units within the structure was interconnected as sheets, resulting in an advantageous general shallow depth. However, an important drawback was observed in the requirement of each sub-unit to maintain complete balance. The failure to achieve this equilibrium led to the inability of the entire structure to retain its intended shape. The structure of the sub-unit prevented the set from retaining form, demanding compression and tensile forces from other sub-unit structures to converge, thereby necessitating the spherical design.



Figure 6: Tensegrity Sub-Unit Dome System

Source: Authors

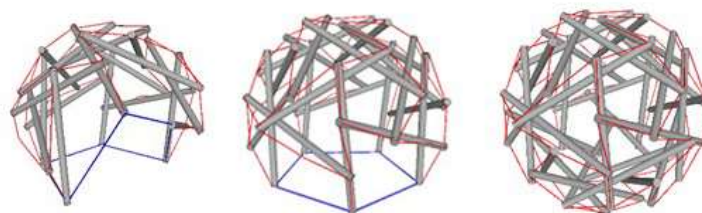


Figure 7: Geodesic Tensegrity Dome

Source: Authors

2) Linear System Tensegrity Structure



Figure 8: Connection of Linear System Tensegrity Sub-Unit

Source: Authors

Tensegrity structure was observed to possess linear expansion properties and its ability to alter the shape was also considered an advantage. However, the structure was unsuitable for surface application due to complex internal connections and binding forces within each sub-unit. The connections were typically bidirectional (forward and backward) in a complete 3D manner, thereby allowing free expansion, contraction, and alteration of shapes. The structure did not require interrelation, albeit at the expense of general structures, depth, distance, and the complexity of the connection force between the cable and compression loads.

3) Self-Repetitive Tensegrity Structure

Self-repetitive tensegrity structure was observed to have versatile shapes and based on a core structural form. It was capable of shape modification but did not achieve optimal efficiency. The type was able to adjust the overall profile height and low points but was unable to alter the length of the main structure. Moreover, the expansion required modifying the length of compression parts within the original force lines. The structure could cover a

large area and modify the shape but the efficiency was compromised based on the previously identified two issues, compared to the preceding types.

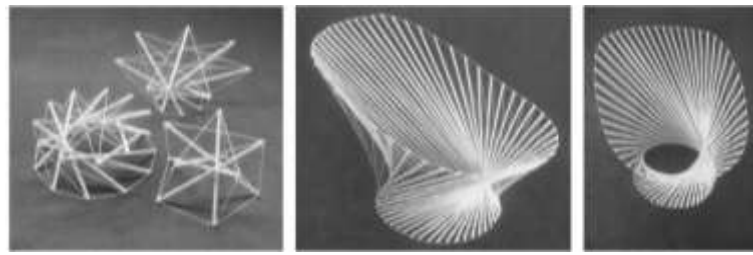


Figure 9: Connection of Linear Tensegrity Sub-Unit System

Source: Marcelo Pars

Form Objective of the Research 3, To design a new type of Tensegrity structure. The analysis of the properties and ability of the structure indicated some limitations in the application in architectural design. This led to the development of new tensegrity structure with characteristics different from the previous ones such as the ability to 1. modify shape and size, 2. cover the area, 3. create shapes considered impossible for the other tensegrity structures, and 4. ensure easy assembly and installation through a modular system.

Table 1: Summary of Properties of the Different Types of Tensegrity Structure

Type	Change shape form	Cover the area	Easy to assemble	Temporary building	Other
Dome	✗	✓	✗	✗	
Linear	✓	✗	✗	✗	
Replicate	✓ ✗	✓ ✗	✗	✗	
New type	✓	✓	✓	✓	shape form



Figure 10: Physical Model Experiment for Tensegrity Structure

Source: Authors



Figure 11: The Tension Produced

Source: Authors



Figure 12: Experimenting with a Full-Scale Physical Model of Tensegrity Structure

Source: Authors

Experiments were conducted by using physical models, both small and scale 1:1, to determine the shapes or patterns for connecting sub-elements in the units of a new tensegrity structure. The results showed that the model was able to manipulate its shape into a predetermined pattern, the general structure was strong and stable, and the process of assembling the parts was simple, making it easier to control the shape. The model also had a feature to add more units without having to complete the system such as tensegrity structure. Furthermore, its line system and ability to cover the area were similar to the dome system in addition to the ability to change the shape of some structures. This means the combination of the properties from different types of tensegrity structure made the new mixed model to be perfect.

The New Body of Knowledge

Figure 14 shows that the previous Tensegrity had only a one-dimensional tension-compression line. Then As in Figures 15, and 16, when adding another layer to the surface of the compression-tensile dimension in the structure, it will be found that such a structure can be formed. In other words, the structure can receive forces in every direction, making this method the key to developing a new type of Tensegrity. The new tensegrity structure examined is different from previous ones because it is designed using connecting subunits within a two-layer tensile surface structure. This knowledge is expected to allow the development of other compression part shapes and the creation of more diverse architectural and space designs. The structure can be formed by adding another layer to the surface of the compression-tensile dimension. This means the model can withstand forces in every direction, thereby serving as the key to developing a new tensegrity structure.



Figure 13: The Physical Model Shows the One-Dimensional Tensile-Compression Line in Former Tensegrity Structure

Source: Authors



Figure 14: Force Pattern of Pre-Existing Tensegrity Structure

Source: Authors



Figure 15: Experiment to Connect the Sub-Units within a Two-Layer Tensile Surface Structure

Source: Authors



Figure 16: Mixed Tensegrity Structure Model

Source: Authors

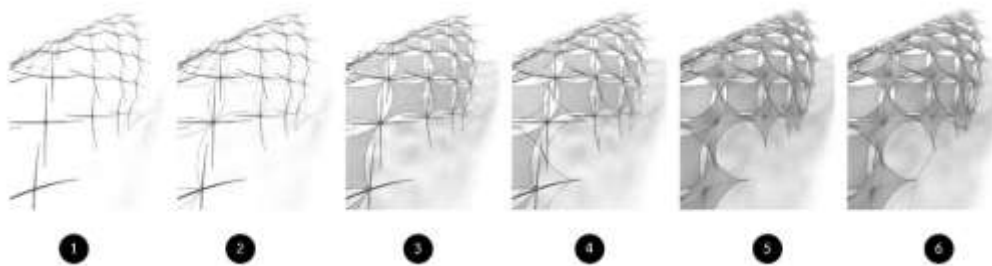


Figure 17: Process to Produce the Mixed Tensegrity Structure Model

Source: Authors



Figure 18: Final Mixed Tensegrity Structure Model

Source: Authors



Figure 19: Double-layer Tensegrity structure model

Source: Authors

By designing the Tensegrity structure to look like a pavilion in the shape of a curved roof due to the characteristics of the curved roof shape. It is considered to be the shape that all 3 Tensegrity systems have ever had. It cannot be shaped like this and the shape of the curved roof is still considered a shape that can be adjusted in size to a certain extent. From the results of the experiment, the Tensegrity mixed system will use guidelines for placing units when increasing the number of Tensegrity dome systems, but there is a system that uses tension ties such as the same as the Tensegrity Linear System. With these two features, the Tensegrity mixed system can increase or decrease the number of units as desired and results in controlling the shape of the structure.

Existing knowledge about tensegrity structure was applied to develop a new model to respond to the form or shape needs in architecture by combining some features from previous types. Tensegrity was structurally designed as a pavilion with a curved roof shape which could not be achieved by any of the three existing systems. The size of the shape could be adjusted

to a certain extent. Moreover, the experimental results showed that the mixed system was designed by using the orientation of a unit associated with an increase in the number of tensegrity structure dome systems. It was also discovered that the model had tensile connections like the line-shaped tensegrity structure. The existence of these two features was expected to allow the new model to increase or decrease the number of units needed, thereby making it possible to control the structural shape.

Discussion of Research Results

Tensegrity structure is often applied in a wide range of works, specifically in structural composite (Motto, 2012) due to its lightweight and flexibility. However, the system connecting individual parts within the structural elements is complex and the assembly process is cumbersome. The advantages are straightforward as indicated by the significant reduction in the mass receiving loads (Ma, Chen, and Skelton, 2022). Meanwhile, there is a limitation in its application for architectural works due to the spatial needs of different shapes and sizes to be met. Every component within the structure is essential and relevant to other elements. This means each piece is required to be gradually integrated, specifically during the connection of the parts. Therefore, this research was conducted to achieve three objectives.

From research objective number 1, it is evident that the origin and history of tensegrity structures can be traced back to two significant figures, namely Buckminster Fuller and Kenneth D. Snelson. The name "tensegrity" originated from Buckminster Fuller's designation, and it is consistent with both Fuller (1982) and Jáuregui (2020), who credited Buckminster Fuller with coining the term in 1955, blending "tension" and "integrity." The development of tensegrity structures, their evolution, and their applications have revealed distinct contributions by Buckminster Fuller and Kenneth D. Snelson. Detailed geometric studies were initially reported by Fuller (1975) and Pugh (1976), while Snelson (1965) made significant contributions to the art style of tensegrity. Tensegrity structures also found quick application in various fields, including architecture, engineering, and robotics (Gomez-Jauregui, Carrillo-Rodriguez, Manchado, and Lastra-Gonzalez, 2023; Liu et al. 2022).

From research objective number 2, the classification of tensile structures encompasses three main categories: 1. Tensegrity Dome Structures, 2. Linear System Tensegrity Structures, and 3. Self-Repetitive Tensegrity Structures. This classification facilitates the selection of suitable applications and can potentially lead to innovative discoveries by combining structural properties to create new forms of tensegrity structures. These new structures may address specific use cases, such as the ability to expand in width and length while effectively covering an area.

From research objective number 3, it was found that it becomes evident that the newly designed tensegrity structure possesses unique advantages. It can expand both in width and length, effectively cover areas, and exhibit structural flexibility. These distinct properties

set it apart from other types of tensegrity structures, making it a versatile solution applicable in various domains including architecture, furniture design, and other product applications.

Conclusion

In conclusion, this research was used to show the methods of designing a new type of tensegrity structure known as the mixed tensegrity structure. The first step was to study the origin and history followed by the classification of currently existing types based on the properties and ability to change the shape direction and the area covered such as the surface. Moreover, the advantages and disadvantages were determined and all relevant data and methods were collected and entered into the design process in order to produce a new type of tensegrity structure with the ability to change size and shape. The general structure was required to have the ability to cover an area, be surface-based, and be capable of creating shapes considered impossible for previous tensegrity structure types to develop. It was also expected to be easy to assemble and install for use in several designs.

Suggestions

From the results of the research, the researcher has the suggestions as follows:

1. The suggestions from the research

From the research result of objectives, it was found that Tensegrity was classified based on the properties and ability to change the shape direction and the area covered such as the surface. The criteria were mainly derived from the need to develop a new type of structure applicable in extensive architectural design with a focus on space layouts requiring a variety of shapes and sizes. This knowledge and method suited architects, engineers, and designers interested in finding a lightweight, wide-span structural design that could change shapes and maintain high stability. The working principle of tensegrity structure was based on ensuring compressive and tensile forces work together. This meant the strength depended on the material selected for compression and tensile parts.

2. The suggestions for future research in this research article

The future research should involve the following issues:

2.1 Tensegrity is a structure that consists of continuous tensile force if any point of the structure is damaged. Whether it is a part that receives compression or a part that receives tension, the overall structure will need help to maintain balance. Therefore, the experimenter should control and install the workpiece in a strong, stable, and careful manner.

2.2 The working principle of tensegrity structure was based on ensuring compressive and tensile forces work together. This meant the strength depended on the material selected for compression and tensile parts. Meanwhile, the strength of the material also increased the possible obstacles encountered during the installation, indicating the need to focus on the type of tools to be used. Tensegrity structure had continuous tensile forces. This showed that

the damage of any part, either compression or tension, could lead to the need to maintain a general balance of the whole piece. It was also necessary for the person experimenting to control and install the workpiece in a strong, stable, and careful manner.

References

- Fraddosio, A., Pavone, G., & Piccioni, M. D. (2019). Minimal Mass and Self-stress Analysis for Innovative V-Expander Tensegrity Cells. *Composite Structures*, 209, 754-774.
- Fuller, R. B. (1982). *Synergetics: Explorations in the Geometry of Thinking*. New York: Macmillan Publishing Co., Inc.
- Gomez-Jauregui, V., Carrillo-Rodriguez, A., Manchado, C., & Lastra-Gonzalez, P. (2023). Tensegrity Applications to Architecture, Engineering, and Robotics: A Review. *Applied Sciences*, 13(15), 1-37.
- Jáuregui, V. G. (2020). *Tensegrity Structures and their Application to Architecture (Vol. 2)*. Spain: Ed. Universidad de Cantabria.
- Koohestani, K. (2012). Form-finding of Tensegrity Structures Via Genetic Algorithm. *International Journal of Solids and Structures*, 49(5), 739-747.
- Liu, Y. et al. (2022). A Review on Tensegrity Structures-based Robots. *Mechanism and Machine Theory*, 168, 104571.
- Ma, S., Chen, M., & Skelton, R. E. (2020). Design of a New Tensegrity Cantilever Structure. *Composite Structures*, 243, 112188.
- _____. (2022). Tensegrity System Dynamics Based on Finite Element Method. *Composite Structures*, 280, 114838.
- Motro, R. (2003). *Tensegrity: Structural Systems for the Future*. London; Sterling, VA: Kogan Page Science.
- Motro, R. (2012). Tensegrity: From Art to Structural Engineering. In *2012 IASS-APCS Symposium* (pp. 14-p).
- Pugh, A. (1976). *An Introduction to Tensegrity*. California: Univ of California Press.
- Skelton, R. E., et al. (2001). An Introduction to the Mechanics of Tensegrity Structures. In *Proceedings of the 40th IEEE Conference on Decision and Control (Cat. No. 01CH37228) (Vol. 5, pp. 4254-4259)*. Orlando, Florida, USA: IEEE.
- Snelson, K. D. (1965). *U.S. Patent No. 3,169,611*. Washington, DC: U.S. Patent and Trademark Office.
- Xu, X., & Luo, Y. (2010). Form-finding of Nonregular Tensegrities Using a Genetic Algorithm. *Mechanics Research Communications*, 37(1), 85-91.