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Investigation of deformation in tensegrity structures across different string materials and dimensions

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Abstract

This experiment investigates the deformation behaviour of various string materials used in tensegrity structures, specifically in a tensegrity table, which is subjected to controlled loading conditions. Six types of strings with different diameters and material compositions were used in the experiment, including braided nylon (3, 4, and 5 mm), monofilament fishing string, braided fishing string, and fluorocarbon string. Measured under incremental loads of 5, 10, and 15 kg, the deformation of each string was observed to correlate with its mechanical characteristics, including stiffness, yield strength, and Young's modulus. The experiment shows that monofilament fishing string shows the least amount of deformation, making it the most structurally stable under various loading conditions, which is related to its material stiffness and minimal cross-sectional area. In contrast, braided nylon and fluorocarbon strings show higher deformation during testing, indicating that braided nylon and fluorocarbon is unsuitable for high-tension applications in tensegrity systems. This experiment offers insight into choosing the best string materials to improve the stability and load-bearing performance of tension structures, especially tensegrity tables.

Keywords: deformation, tensegrity, string dimension, string material

1. Introduction

A tensegrity table is a system that relies on the balance between tension and compression elements in the structure to maintain stability and structural integrity. The lightweight and self-supporting nature makes these structures ideal for use in many different fields, such as aerospace, robotics, and architecture [1]. In aerospace, tensegrity structure is used for satellites and space habitats since it is lightweight and resilient [2]. In robotic tensegrity structure is used in the field of soft robotics, by combining 3D printing with sacrificial molding, which removes the need for manual assembling and enables a smooth integration of flexible tendon networks and strong struts [3]. Similarly, in architecture, tensegrity structure is seen to be used for their continuous tension and discontinuous compression, which improves the flexibility and resilience of architectural designs [4]. Moreover, the choice of strings used for a tensegrity table plays a crucial role in determining the strength and structural stability of the table, since different string materials possess unique mechanical properties, such as tensile strength, elasticity, and durability, all of which can impact the performance of the table [5],[6]. The use of different types of knots in tying the string to the table also affects the overall strength of the table itself, as some knots can increase or decrease the strength of the rope used [7].

Studies have indicated that braided string with specific structural characteristics improves tensile strength to raise the overall structural integrity and structural stability. When using polyvinyl alcohol (PVA) yarns, it is observed that braided strings significantly enhance the structural performance, wth testing showing that a standard size 6 PVA yarn exhibits a tensile strength of 316.2 MPa, whereas the size 6 braided string demonstrates a higher strength of 398.5 MPa [8]. Likewise, it is found that braided strings with different angles have different strengths depending on the angle used in the braiding, such as braided angles of 25° and 30° of a braided composite have an ultimate tensile strength (UTS) of 40% whereas for 45° braided composites it is 50% of the UTS [9]. Apart from that, research conducted on synthetic fiber ropes, such as High-Modulus Polyethylene (HMPE) and polyester, shows that environmental exposure, repeated stress cycles, and load history all affect the way tensegrity structures perform in the long run [10]. Furthermore, finite element analysis and the Lagrangian method to formulate a nonlinear equilibrium equation have been utilized to analyse the best string configurations, stress distribution, and stability on tensegrity structures [11], [12]. Other than that, because of the superior strength-to-mass ratio, some studies have focused on mass reduction of the tensegrity system by proposing minimal-mass design approaches through additive manufacturing techniques, to create lightweight tensegrity structures without disturbing structural integrity [13], [14].

Comparative studies of tension-based systems also show the advantages of the tensegrity structure of having a strength-to-mass ratio over conventional structures, such as truss structures, which are widely used in bridges and roofs, and precast concrete beam and column structures that are used to carry loads and distribute forces, but both of these structures have the drawback of being heavy and less adaptable [15], [16]. Additionally, with the advancement in additive manufacturing, such as the 3D printing method, the production of tensegrity structures with high precision has become highly feasible [17]. Likewise, with the use of composite materials and advanced fiber ropes, the manufacturing of a lightweight and strong tensegrity structure has also become easier [18], [19]. However, the combined effects of material properties, knot techniques, and environmental exposure must be researched further to gain insight into future designs of robust and efficient tensegrity tables [20].

This study aims to further research the impact of varying string on the overall structural strength of a tensegrity table. The research specifically focuses on analysing the string deformation that happens under various loading conditions, since the string experiences stress and strain during use. Understanding how different strings react to the various loading, is essential in finding the optimal string to be used for the tensegrity table. Evaluating a range of string types with distinct properties, such as yield strength, Young's modulus, and stiffness, contributes to the research aims to find the best types of string that are able to increase the strength of the tensegrity table.

2. Methods

Material and Apparatus

There are 3 apparatuses used in this experiment tensegrity table, the calliper, and the weights, as depicted in Figure 2. In this experiment, a tensegrity table is used as a tool to analyse different string strengths by having the strings hold up the tensegrity table, while a known load is applied to the tensegrity table. After applying the load, the string experiences deformation, which is measured using a vernier calliper. Additionally, the string materials used for the experiment would be the 6 different strings, namely braided nylon at 3, 4, and 5 mm, monofilament string, braided fishing string, and fluorocarbon, as shown in Figure 1.

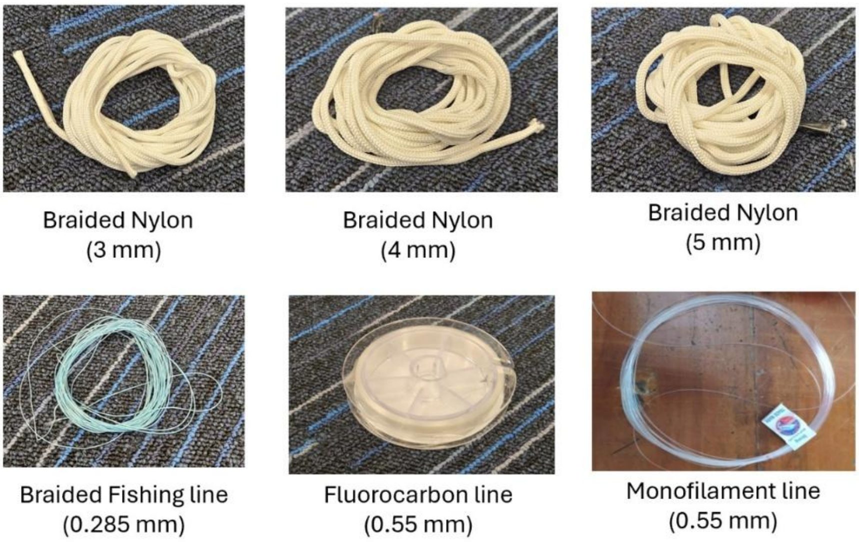


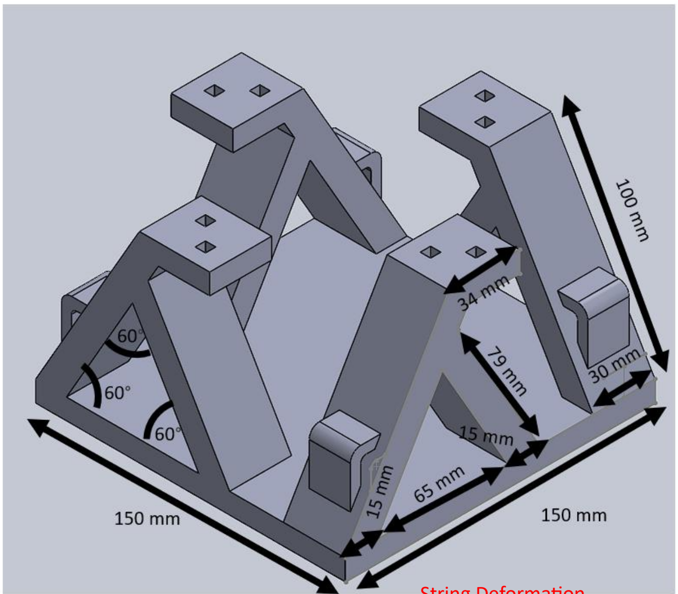
Figure 1. The different strings used within the experiment

Figure 2. Weights used in this experiment

Experimental Method

The experiment conducted in this research paper involves testing different strings in the setting of a tensegrity strength structure to obtain the string best suited for use in a tensegrity setting withstanding a significant load to structure mass ratio; a ratio of 1:15 is determined to be sufficiently acceptable while maintaining stability that is measured by the deformation the string generated when subjected to the maximum determined loading. With a mass of 1 Kg, the strings would need to hold a maximum load of 15 Kg

The experimental method started by designing the best tensegrity table that can be incorporated into the testing procedure. To create the tensegrity table, several design factors needed to be considered, such as having a knot hole that allows for all string specimens to be tied to while maintaining the tension state, allowing the loads to be placed in a stable configuration, as well as having enough room for the strings to deform without being obstructed in said process. Hence, the design shown in Figure 3 was created using SOLIDWORKS.



String Deformation

Figure 3. 3D model sketch of the tensegrity strength table on SOLIDWORKS

The tensegrity structure was created using a 3D printer to experiment. The table is printed from PLA at 75% density with a hexacomb pattern infill at a speed of 180mm/s and organic support on an Anycubic i3 Mega 3D printer. The structure is used as the medium and the controlled variable for the experiment. Several weight scales totalling 15 Kg, with an interval of 5 Kg, are used as the independent variable. The experiment was conducted by changing between the different strings then the deformation was measured as the dependent variable. As the strength of each string is affected by the knot of the strings, the knot is chosen to be the same throughout the experiment. The chosen knot is in the form of a "Clove hitch," which is easy to apply and has versatile applications. To ensure the accuracy of the findings from the experiment, a vernier calliper is used to measure the deformation of the structure. The experiment was conducted 3 times for each loading while taking into account potential human error from the loading placement by having the average deformation between the 4 sides of the tensegrity table. Lastly, to investigate the data further, the string material is analysed using its material property, which is the Young's modulus, as it might be relevant to use for investigating the deformation of the string materials used, which allows for plotting the relationship between the string.

3. Result and Discussion

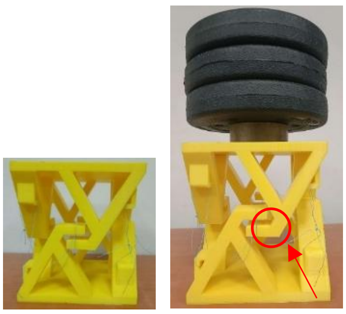


Figure 4. Before (left) and after (right) loading

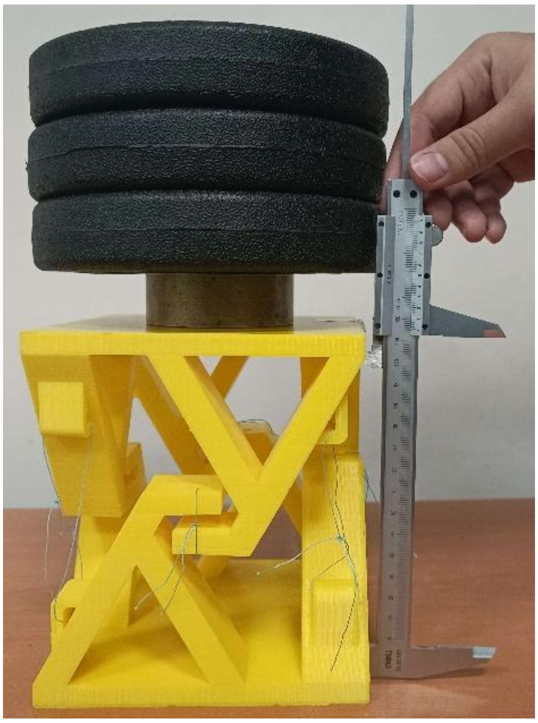


Figure 5. Deformation measurement

The tensegrity table experiment is conducted by putting different amounts of weight on the table, as shown in Figure 4 The weight is put slowly on the table with an increment of 5 kg until 15 kg. The string then starts to deform, as shown on the red circle in Figure 4 on the right. At each weight increment, the deformation of the string used is measured using the vernier calliper, as shown in Figure 5, on all sides of the tensegrity table, since the string holds the tensegrity table on 4 sides. The deformation measurement is then averaged and shown in Table 1.

Table 1. Experimental Result

No.	Types of String (Diameter)	Weight (Kg)	Deformation 1st (mm)	Deformation 2nd (mm)	Deformation 3rd (mm)	Average Deformation (mm)
1	**Braided Nylon (5 mm)**	**5**	14.32	9.96	15.82	13.37
		10	19.98	14.24	19.78	18
		15	39.32	27.38	22.74	29.81
2	**Braided Nylon (4 mm)**	**5**	10.78	7.40	11.42	16.15
		10	15.76	10.58	18.58	10.67
		15	21.92	14.03	39.36	23.12
3	**Braided Nylon (3 mm)**	**5**	15.58	9.92	8.10	11.2
		10	15.18	16.6	12.3	14.69
		15	18.28	24.4	17.28	19.99
4	**Monofilament (1.38 mm)**	**5**	2.60	3.50	4.28	3.46
		10	5.30	5.72	6.54	5.85
		15	8.90	8.38	8.80	8.69
5	**Braided Fishing**	**5**	0.92	7.18	2.84	3.65
		10	7.76	10.16	4.40	7.44

No.	Types of String (Diameter)	Weight (Kg)	Deformation 1st (mm)	Deformation 2nd (mm)	Deformation 3rd (mm)	Average Deformation (mm)
	String (0.28 mm)	**15**	11.32	13.04	5.92	10.09
6	**Flurocarbon (0.55 mm)**	**5**	**Failed at 10 kg**			
		10				
		15				

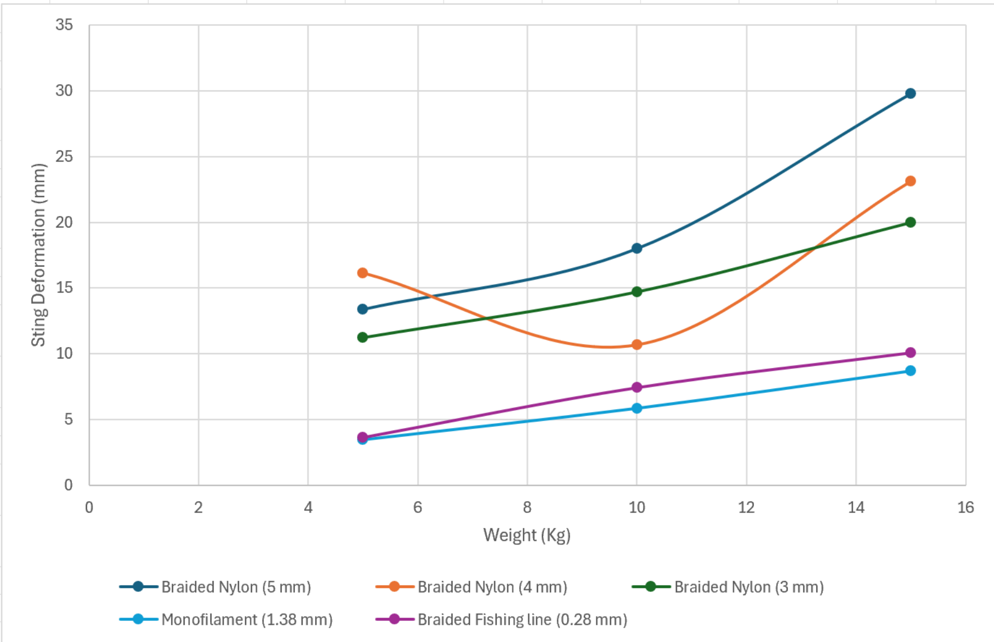


Figure 6. Deformation experienced by each string

To visualise the deformation experience of all the strings, a chart was created using the deformation data from Table 1, as shown in Figure 6, where all the strings have a steady increase in deformation experience, with the lowest deformation experience by the Monofilament string (1.38 mm) across all the weights, followed by the braided fishing string (0.28 mm) and the different braided nylon with a diameter of from 3 to 5 mm. This chart shows that as the diameter increases, the deformation of the strings also increases. For a tensegrity table, it is better to use a string with a lower diameter since it deforms less than a string with a larger diameter.

Table 2. Young's Modulus of each string

No.	Material	Young's modulus
1	Braided nylon	3.79 GPa
2	Monofilament	4.132 GPa
3	Braided fishing string	35 GPa
4	Flurocarbon	3 GPa

As shown in Table 1, braided nylon string (3 mm, 4 mm, and 5 mm diameters) exhibited more significant deformation, especially under higher loads. The 5 mm variant has an average deformation of 29.81 mm at 15 kg. When compared to the 4mm and 3mm at the same load (15 kg), which have an average deformation of 23.12mm and 19.99mm, it is clear that thicker string tend to have more deformation because the woven structure and the low stiffness from the Young's modulus of the strings which is 3.79 Gpa shown in Table 2, which makes the strings more elastic. This characteristic makes the braided nylon string better for applications requiring energy absorption or shock mitigation by making the string able to deform more. However, this increased deformation makes the strings less ideal for use in a tensegrity table, where minimal deformation on the string is essential in maintaining structural stability of the structure.

Other than that, the string of the tensegrity structure must not experience large deformation to maintain its stability and structural integrity. In the case where the string deforms too much, it creates an imbalance in the table, which allows it to collapse. One example of this would be in Figure 7. As one of the strings deforms too much, it allows for an imbalance and leads to the collapse of the table as a whole, as the table no longer distributes the load evenly. Within the experimental testing, the 6th string, Fluorocarbon, is observed to have failed at a loading of 10 Kg. The string could not hold the tensegrity table as intended. As the string is being loaded under 10 Kg of mass, one of the side strings gave out because the knot slipped, and the entire structure toppled. The result is found after reaping the experiment twice, which yielded the same result of the fluorocarbon string failing, conclusively showing that fluorocarbon is not suited for use as a tensile table support in this setting. Additionally, the failure highlights the importance of proper knot selection and tying techniques in ensuring the strength and stability of the tensegrity table.

Figure 7. Flurocarbon string failing

Besides that, another interesting case is the braided fishing string (0.28 mm). Despite its small diameter, which initially showed low deformation at 5 kg (3.65 mm) and a Young's modulus of 35 GPa, suggesting desirable performance. But shows inconsistent results at 10 kg (7.44 mm) and 15 kg (10.09 mm). This inconsistency is likely due to the challenge of securely tying the string to the tensegrity structure on a string with a small diameter, as it does not allow for the string to be fastened as well as its thicker counterparts. Even after repeated attempts to tie the string securely, it remained slightly loose, as shown in Figure 4 before loading, which allows for more movement and slippage to occur when higher loads are applied. As a result, the string deforms more easily as the load is increased, highlighting once again the importance of the knot used in the tensegrity table and uniformity of the tension.

Lastly, the experiment found that among all the strings tested, the monofilament fishing string displayed the smallest deformation across all loads (3.46 mm at 5 kg, 5.85 mm at 10 kg, and 8.69 mm at 15 kg) as seen in Table 1. This highlights the good combination of high Young's modulus (E) and small area (A) of the strings, which makes deformation of the string minimal. Monofilament fishing is typically made of a single-strand nylon and is widely used because of its versatility and affordability [21]. Furthermore, monofilament string exhibits high to moderate stretch, which helps in absorbing shock and reduces the likelihood of string breakage [22]. Furthermore, during testing, the monofilament string was able to be securely secured to the tensegrity table, which makes it better at resisting deformation. These are some of the reasons why it is able to hold different weights and have the smallest amount of deformation, as it is designed to absorb shock given to it, making this string the perfect candidate, as it strains the least while still a significant tension strength.

4. Conclusion

To obtain the optimal string for use in a tensegrity structure, the material must exhibit a high Young's modulus, have good compatibility with the knot used, and have a minimal cross-sectional area to limit deformation under load. The experimental findings demonstrated that a fluorocarbon string is unsuited for use in a tensegrity strength table. The material experiences complete failure as the table topples under the load. Monofilament fishing string, on the other hand, outperformed other tested materials by maintaining the lowest average deformation across all loading scenarios. With a maximum average deformation of 8.69 mm, monofilament fishing string is the most suitable candidate for tensegrity applications. Its superior mechanical performance is attributed to its high stiffness and small diameter, which together minimize strain and help preserve the structural balance. Conversely, the thicker braided nylon string, although strong, showed significantly higher deformation due to its greater elasticity and lower stiffness. These insights highlight the importance of material selection and dimensional optimization in tensegrity design. Future studies could explore more advanced synthetic fibers, analyse the impact of environmental conditions, and investigate additional knotting techniques to further enhance performance and durability in real-world applications.

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