Evaluation of Structural Materials for Space Elevator Applications

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Abstract - *A space elevator is a concept that is being pursued by many researchers around the globe. One of the space elevator's most critical components is the tensile load-bearing cables, which will require immense strength. This paper explores three different materials for space elevator applications in a wire rope design as load-bearing elements of a space elevator. Finite-Element Method (FEM) is used to numerically model the stress-strain behavior of wire ropes of Steel, Titanium, and Carbon Nanotubes under the tensile loading conditions of a space elevator. It was found that the strength-to-weight ratio is the highest for Carbon Nanotubes; hence, it was the only material suitable for such an application. Such a study can be helpful for designers of future space elevators once the manufacturing capabilities of Carbon Nanotubes scale up to meet such demands.*

Key Words: Space Elevator, Finite Element Method, Carbon Nanotubes

1. INTRODUCTION

The era of space exploration has never been as exciting as today and satellites are being used in almost every field now. With the rising number of satellites and their applications, the process of improving the efficiency of launching a satellite has become an area of interest for a lot of research. A space elevator is one such proposed idea that can revolutionize the placement of satellites in lower earth orbits with a significant cost reduction.

Due to the rising cost of launching space shuttles, the requirement of a space elevator is well justified [1]. A detailed review of the entire concept of the space elevator and its components is documented by Edwards in his book [2]. This application attracted researchers' interest when J Pearson [3] solved the problem of buckling by proposing a design of a cable entirely based on tension which was considered in most of the future research in this domain. Space elevators in concept will use a long combination of cables with one end on earth and the other one tied with counter weight in the lower earth orbit or space. The center of mass of such a system would also be in space given the counterweight location. In this arrangement, the structure would remain rigid due to the gravity and centrifugal force acting in the opposite directions. Due to these opposite forces, the structure would be under immense tensile load as opposed to the compressive load which was thought initially during the conception days of the space elevator. Apart from strength, the space elevator cable must also be highly conductive as there will be friction produced due to the relative motion of the elevator on the cable, and hence heat will be generated in high amounts. In space with no ambient atmosphere to dissipate heat, the temperature of the cable may reach very high in a short period and may lead to catastrophic damage or failure. Most structural applications will utilize twisted wire ropes in place of rods for better flexibility and strength-to-weight ratio.

Edwards [4] gave a comprehensive design of the elevators considering different issues like tapering of the cable, energy sources, and collisions with meteors or space debris. In recent years, the focus has been mostly on gauging the strength of the rope by identifying novel materials like carbon nanotubes [5].

In this work, an ultimate tensile test of a twisted cable is simulated for different materials to evaluate the feasibility of a space elevator. A numerical model is created with a tensile load applied on one end of the cable while keeping the other end fixed. Finite element method is used to analyze the effect of tensile loading on Von-mises stress in a twisted cable design. In this way, the working conditions of a space elevator cable are simulated using the learning edition of Abaqus software. Three materials were taken into consideration for this study: Steel (AISI 430), Titanium (Ti-6Al-4V), and Carbon Nanotubes.

2. METHODOLOGY

A uniform tensile strength (UTS) test is one of the most reliable and widespread methods of evaluating the mechanical properties of a material. In a UTS test, the specimen is pulled in different directions to impart tension in the specimen and measure elongation as we do it till the specimen breaks apart. The output of the test is a stress-strain curve that governs the behavior of the material under tensile loading. The tensile strength is an intensive property and hence can be evaluated with small specimens as well as tensile tests. Since it is time-consuming and expensive to conduct a physical tensile test of different materials, numerical simulations are performed to get the results.

Three materials are taken into consideration for the same design and load calculations are made. Low carbon steel was taken as it's a low-cost structural material widely used with large manufacturing facilities all over the world. Titanium was the second choice as the tensile strength was one of the highest in common materials. The third material is carbon nanotubes which have theoretically the highest strength of the existing materials. The table below gives the values of properties used in the simulations.

A space elevator system can utilize multiple twisted cable systems to reduce the load on a single member. One single twisted cable is analyzed in this work to estimate its tensile strength.

The specimen for the simulation is taken to be composed of a homogeneous material with a uniform cross-section. It is also assumed that a pure unidirectional tensile load is acting on the specimen and the process is taken to be isothermal.

In a uniform tensile test, we can define the following as:

- Linear strain

$$\varepsilon_{lin} = \frac{\Delta L}{L_0} \leq \varepsilon_u \qquad (\varepsilon_u = uniform\ strain)$$

- Logarithmic ("true") strain

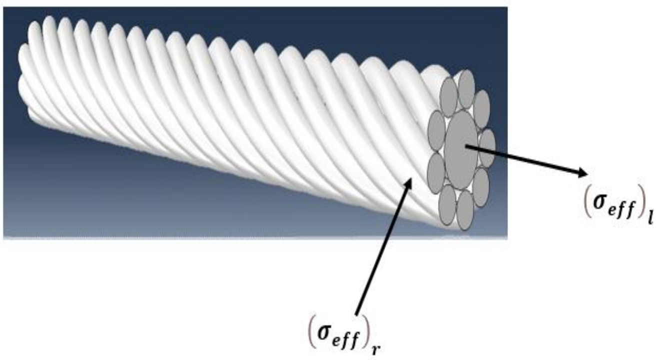
$$\varepsilon_{log} = ln\frac{L}{L_0} = ln(1 + \varepsilon_{lin})$$

- Nominal ("engineering") stress

$$\sigma_{nom} = \frac{F}{A_0} = \frac{F}{W_0 B_0} \leq R_m = \frac{F_{max}}{A_0} \qquad (R_m = tensile\ strength)$$

The simplest equation to correlate true flow stress (σ) and true plastic strain (ϵ_P) is given by Holloman [6] using a strength coefficient (K) and a strain-hardening exponent (n)

$$\sigma = K{\epsilon_P}^n$$



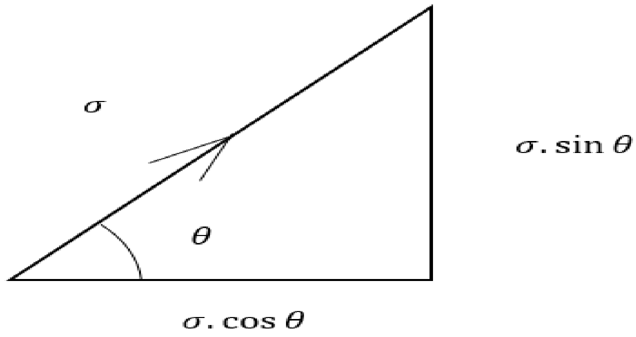
$$(\sigma_{eff})_l = \frac{\sigma.A_c + \sigma.n.sin\theta.A_p}{A_{eff}}$$

σ = stress (out of plane stress due to uniaxial loading)
A_p = Area of peripheral wire
n= number of wires
A_c = Area of middle circular wire

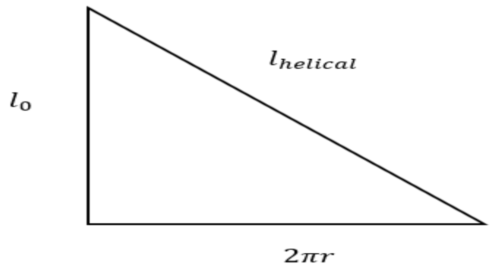
Boundary conditions and loading:

- Encapsulated boundary condition on left side
  - U1 = U2 = U3 = UR1 = UR2 = UR3 = 0
- Uni-axial tensile loading on right side (Z-direction)
  - U3= Strain/Displacement/Force

$$A_{eff} = \sigma_{eff}\ (\,tensile)$$



The cos component will become compressive and therefore, compressive forces will act over whole central section which is helical in shape.



We can calculate the compressive force as the following:

$$(\sigma_{eff})_{radial} = \left(\sigma.\cos(2\pi r).\sqrt{l_0^2 + (2\pi r)^2}\right)$$

2.1 DESIGN OF THE CABLE

As seen in figure 1, the specimen is a twisted cable with a straight core. The dimensions of the cable are mentioned in figure 1(b).

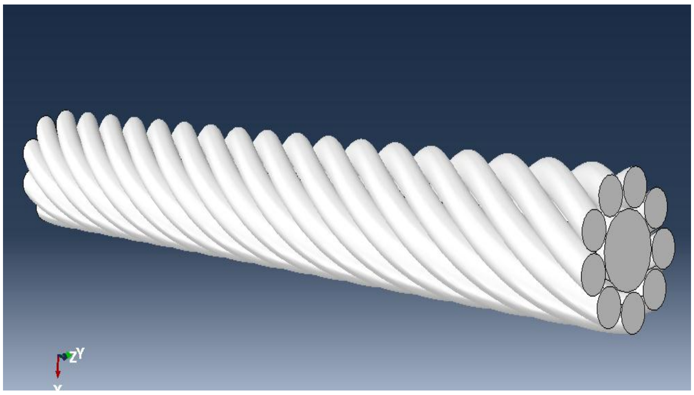


Figure 1 : An image of a twisted cable used for FEM simulations

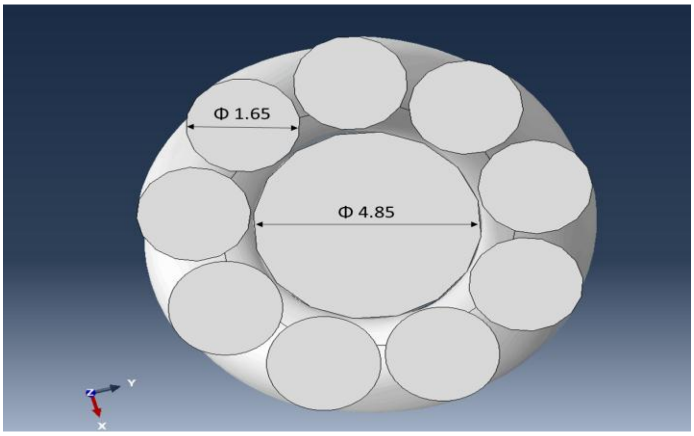


Figure 2: Model cross-section with dimensions

Figure 1 and figure 2 represent the outlook offering twisted wire to be used for finite element modeling simulation part a represents the complete structure of a twisted wire cable and Part B represents the cross-sectional dimensions.

2.3 MATERIALS PROPERTIES

Properties	**Low carbon steel**	**Titanium**	**Carbon Nanotubes**
Density (Kg/m3)	8000	4500	1750
Young Modulus (GPa)	200	113	183
Yield stress (MPa)	250	36	90
Poisson ratio	0.275	0.342	0.27
Strain hardening coefficient	0.26	0.18	0.35

2.3 DESIGNS OF SIMULATIONS AND BOUNDARY CONDITIONS

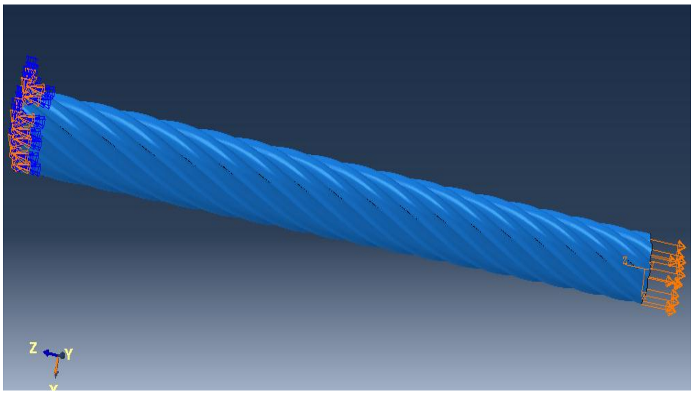


Figure 3: Model with fix boundary condition on left side and axial loading along the length (right side) of the wire for FEM simulations

A fixed boundary-based condition on the left side and a free uniaxial loading along the length is represented in figure 3 as a result of the FEM simulations.

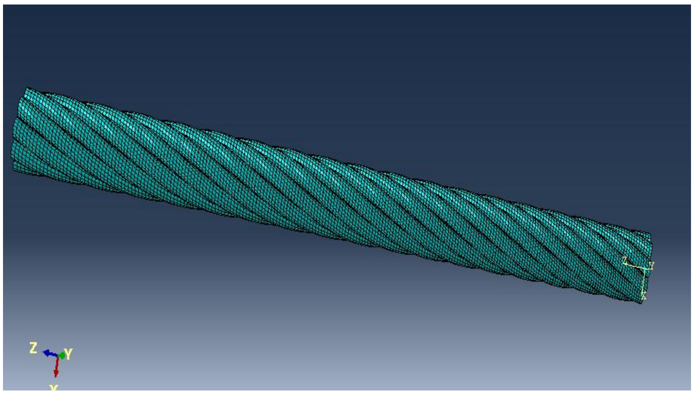


Figure 4: Model with 3D meshing and C3D8R (An 8-node linear brick, reduced integration, hourglass control) element type

Figure 4 represents the 3-dimensional meshing of the twisted rope with general purpose linear brick element (C3D8R).

3. RESULTS AND DISCUSSION

3.1 DISPACEMENT OF THE SPACIMENT

The color-coded FEM simulation results of the displacement of the twisted rope are represented in Figure 5. It can be seen that the displacement decreases along the length of the wire. Maximum displacement is observed on the right-hand side where the load is applied, and zero displacement is obtained on the fixed end.

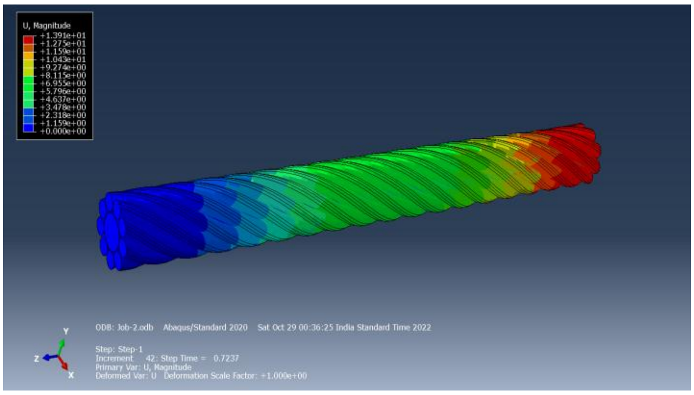


Figure 5: Displacement of the twisted rope

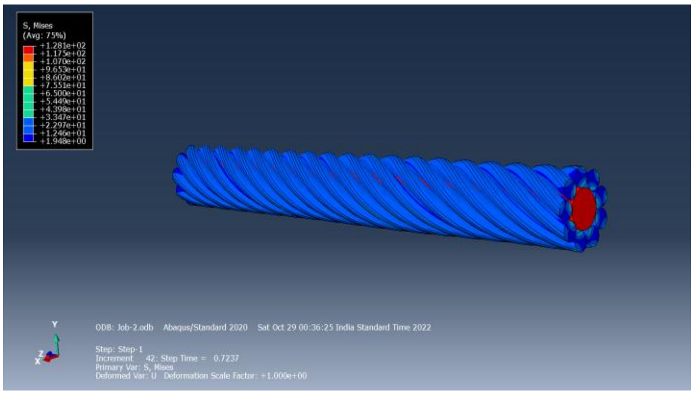


Figure 7: Von mises stresses of the twisted rope

Figure 6 represents the displacement trend caused by the wire along the length. As the distance along the wire increases, its displacement per element decreases. This is because the wire displacement depends on the strain, which is a function of the length or distance along the wire. If we recall the mathematical expression for the true strain of a material, it can be seen that the strain (and hence displacement) is inversely proportional to the initial length.

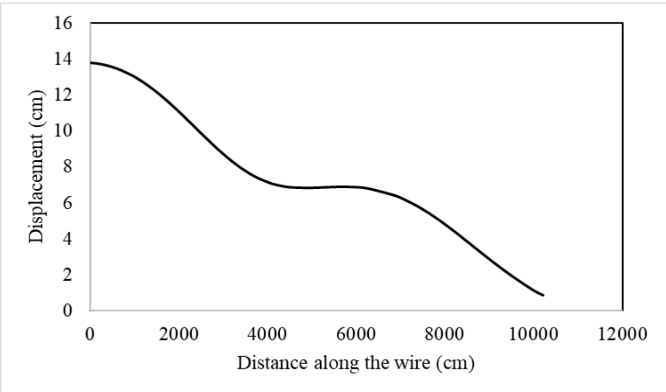


Figure 6: Displacement of twisted wire as a function of it distance

Figure 7 and 8 represent the Von Mises stresses and the pressure on the twisted rope. Von mises is maximum in central rope, whereas pressure is maximum in peripheral rope.

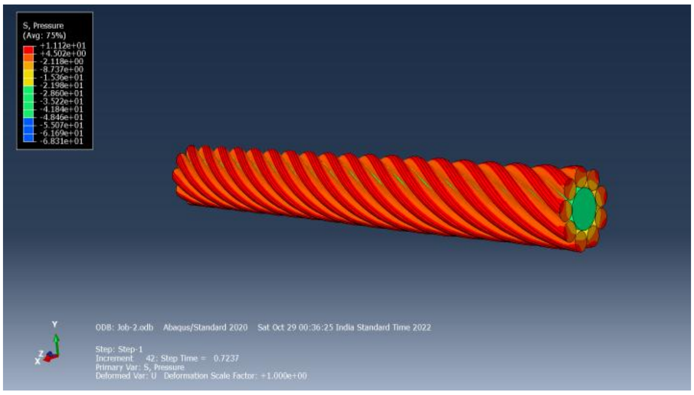


Figure 8: Pressure on the twisted rope

Figure 9 represents the stress vs strain behavior of low-carbon steel for a circular and a wire rope case. Here it can be seen that the slope in the elastic region (i.e., young's modulus) is higher in the case of twisted wire rope. Although there is little difference between the yield strength and tensile strength in both cases, the yield ultimate tensile strength is almost double for the case of twisted wire strength.

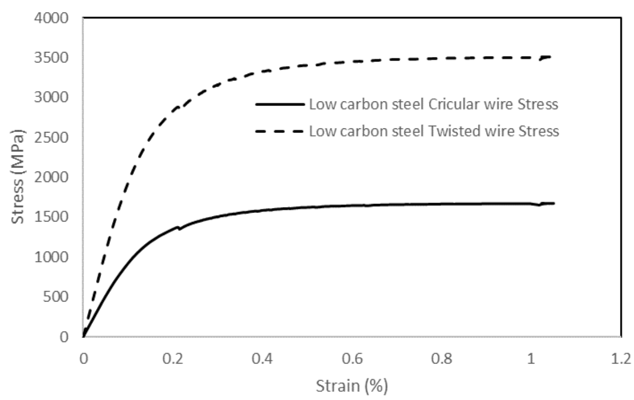


Figure 9: Stress-strain plot of low carbon steel circular wire and twisted wire stress

Figure 10 represents the stress vs strain behavior of Ti6Al4V alloy for a circular and twisted wire case. Here also, just like steel, it can be seen that young's modulus is higher in the case of twisted wire. Despite little difference between the yield and tensile strength for circular and twisted wire stress cases, the yield strength (and also the tensile strength) of the twisted wire case is three times that of the circular wire counterpart.

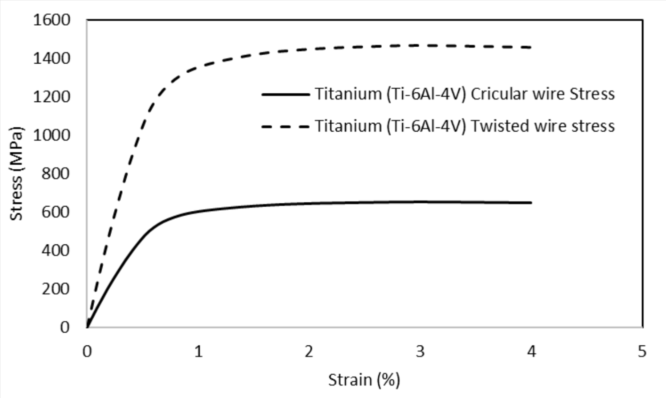


Figure 10: Stress-strain plot of low carbon steel circular wire and twisted wire stress

So, as far as metallic alloys are concerned, twisted configuration exhibits better tensile properties than circular case.

Figure 11 also shows the trend commensurate with the case of metallic alloys. here as well the stress is always on the higher side for the twisted wire system as compared to the circular wire counterpart. So, all the above figures point to results that despite the choice of material the tensile property is much better for the twisted wire configuration.

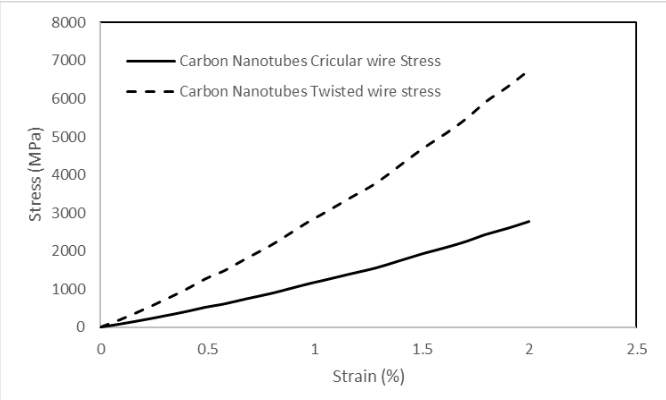


Figure 11: Stress-strain curve for the carbon nanotubes for the case of circular and twisted wire stress

Figure 12 is a composite view of the tensile behavior of low-carbon steel, Ti-6Al-4V alloy, and the carbon nanotube. While it is well understood that the tensile behavior for the twisted wire case is always on the higher side irrespective of the choice of material but adding to it, carbon nanotube exhibits the highest strength as compared to the other choices. On the other hand, Ti-6Al-4V exhibits the best ductility but this comes with a penalty on its strength. Low carbon steel is quite a balance between both strength and ductility as it exhibits an optimal combination of both better tensile strength and reasonable ductility till fracture.

The maximum stress that was experienced without any reduction in the cross-section of the specimen was with carbon nanotubes.

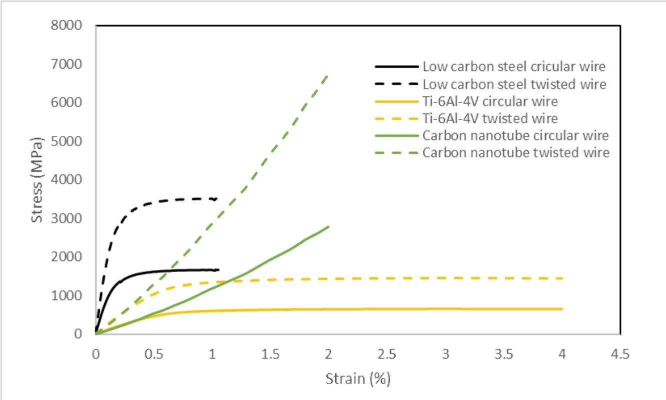


Figure 12: Stress-strain curve for the case of circular and twisted wire stress for all the choices of material

Finger 13 is a comparative measure of the strength-to-weight ratio for the circular and twisted wire configuration for steel titanium alloy and carbon nanotube. Steel exhibits the poorest strength-to-weight ratio among all the 3 cases for both circular and wire configurations. Carbon nanotube stands to be the best with the highest strength-to-weight ratio of approximately 3.8(which is the highest among all the cases). Another important observation is that irrespective of the choice of material here as well the strength-to-weight ratio for the case of the twisted wire system stands to be better than a circular wire configuration.

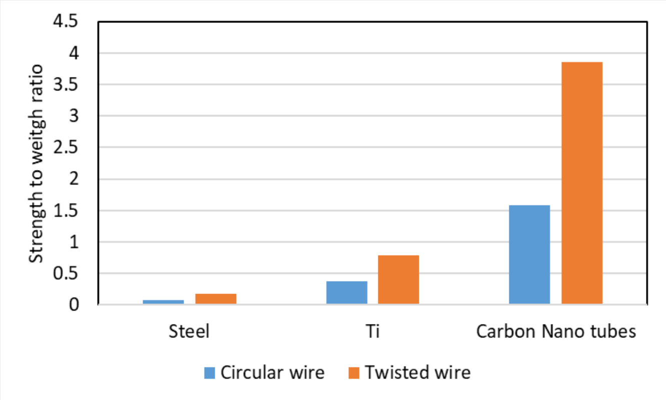


Figure 13: Strength to weight ratio of circular and twisted wire for steel, Ti alloy and carbon nanotube

4.CONCLUSION

A space elevator is a fascinating concept requiring considerable research and engineering effort. This work is one such contribution to these efforts where the load-bearing structures of the space elevator were analyzed. A comparison was made between constant cross-section cables are wire ropes to evaluate the higher load-bearing option of these. Additionally, three different materials were considered for the load-bearing analysis: Steel, Titanium, and Carbon Nanotubes. Finite-element analysis was performed using the Abaqus software for evaluating the tensile failure load of rods and twisted wire ropes. The stress-strain curve and the strength-to-weight ratio were calculated for all the cases and materials, and relevant analysis was performed.

It was observed that the maximum stress reached in twisted wire ropes of low-carbon steel was more than twice that of the circular cross-section specimen. Similar observations were made for Carbon Nanotubes and Titanium as well. The strength-to-weight for low carbon steel was lower than 0.3; for Titanium, it was more than double with a value of around 0.75. The maximum strength-to-weight was obtained for Carbon Nanotubes with a tremendous value of more than 3.75. This indicates that Carbon nanotubes are the most suitable for Space Elevator load-bearing structures among the existing materials. However, there is yet to be an existing prototype of a rope long enough to be used in structural applications using exotic materials like carbon nanotubes. Therefore, any development in the field of structural materials for space elevators will require the development of manufacturing capabilities for carbon nanotubes at a large scale. The present work can help engineer the load-bearing elements when the capability of manufacturing Carbon Nanotubes is developed to large extents.

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REFERENCES

[1] Swan, Cathy W., and Peter A. Swan. "Why we need a space elevator?" Space Policy 22.2 (2006): 86-91.

[2] Edwards, Bradley C., and Eric A. Westling. The space elevator. BC Edwards, 2003.

[3] Pearson J 1975 The orbital tower: a spacecraft launcher using the Earth's rotational energy Acta Astronautica 2 785-799.

[4] Edwards, Bradley C. "Design and deployment of a space elevator." Acta Astronautica 47.10 (2000): 735-744.

[5] Pugno, Nicola M. "On the strength of the carbon nanotube-based space elevator cable: from nano- to mega-mechanics." arXiv preprint cond-mat/0601668 (2006).

[6] Bowen, A. W., and P. G. Partridge. "Limitations of the Hollomon strain-hardening equation." Journal of Physics D: Applied Physics 7.7 (1974): 969.