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Carbon Nanotubes as a Material for a Space Elevator Cable

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The poor economic and environmental sustainability of rocket-based transportation into space has promoted enthusiasm in the development of an alternative method of traveling into space, a space elevator. The method, originally purposed in the 1960s and 1970s, had been abandoned due to a lack of material of sufficient strength until recently, when the discovery of a strong, light allotrope of carbon resurrected the idea. Carbon nanotubes were discovered in the 1991 by Japanese Scientist Sumio Iijima and consist of a layer of graphene wrapped into an approximately 1nm diameter cylinder (Adams 2000; Dekkar 1999). Research into the unique properties that carbon nanotubes posses have lead to speculation about the potential application of carbon nanotubes in the distant future. Likewise, this paper will speculate upon the current and potential properties of carbon nanotubes relative to the material requirements predicted for a space elevator, as actual construction is not likely to be realized in the near future.

A space elevator is a tether anchored to the surface that reaches beyond geosynchronous orbit (35,786 km), designed to transport people and materials into space by utilizing a system of vehicles to scale the cable. A counterweight located beyond geosynchronous orbit would provide increased centrifugal force to subdue gravity and keep the cable up, however, the tension in the cable would be impossible for any common material to reasonably endure. For this reason, carbon nanotubes are being considered the only material strong and light enough to withstand the stress and strain the space elevator would experience.

Tensile Strength and Taper Ratio

The tension experienced in a cable extending from the surface into space varies depending on the altitude and the material used for construction, however, in order to achieve this feat on a reasonable scale, the material used would require a high strength and low density. The strength of a material can be determined by examining the relationship between various physical properties and the way the material behaves. One particular relationship is tensile strength. Tensile strength is the maximum tension a material can tolerate before failing or breaking and is characterized as stress (force per unit area), which is measured in pascals. Carbon nanotubes posses a tensile strength ranging from 70 to 120 GPa, which is extremely large when compared to steel (0.4 GPa) and Kevlar (3.6 GPa) (Moe 2006). Additionally, carbon nanotubes are substantially less dense than steel and Kevlar, with a density of 1300 kg/m^3 compared to 7900 kg/m^3 and 1440 kg/m^3 respectively (Edwards 2000).

It is the ratio between tensile strength and density that is key when considering the design of the space elevator as the strength-density ratio directly influences the taper required in the cable (Edwards 2000). (A taper in context with a space elevator is the ratio of the diameter of the cable in geosynchronous orbit to that of the diameter on the surface.) The cable of a space elevator must taper in order to account for the change in stress, and therefore the change in strength required to support the stress, at different

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points along the cable; if tapered incorrectly, the cable will break. This dependency on tapering means that a space elevator may theoretically be constructed using any material commonly available today so long as it is tapered correctly. For example, since the stress a tether made of steel would need to withstand at the point of highest stress, geosynchronous orbit, is 383GPa, the taper ratio in the cable would have to be 1.7×10^{33}, while a cable made of Kevlar would need to withstand 70 GPa and would require a taper ratio of 2.6×10^{8} (Pungo 2013). These taper ratios are extremely large in contrast to a cable grown from carbon nanotubes, which would have to withstand a stress of 63 GPa, but would only require a taper ratio of only 1.9 (Pungo 2013). The reason a space elevator requires carbon nanotubes and not steel or Kevlar, however, is because the mass of the cable is proportional to the magnitude of the taper ratio. To construct a space elevator out of steel and Kevlar, the cable would require a diameter of greater than 1mm at the surface and a diameter of greater than 2 km at geosynchronous orbit (Smitherman 1999). This would equate to a tether of mass magnitudes greater than 6.0×10^{12} tonnes if made from steel or Kevlar. These masses and diameters are unreasonable. A carbon nanotube tether, however, would only require a diameter of 0.15mm at the surface and 0.26mm at geosynchronous orbit, with a mass of 1.0×10^{8} tonnes (Smitherman 1999). The tensile strength- density ratio of carbon nanotubes is always increasing as new limits of the material is discovered, however, when considering the possibility of a space elevator, the defects of carbon nanotubes must also be considered.

Carbon Nanotube Defects

Although a space elevator grown from perfect carbon nanotubes is ideal, in reality, the strength of a carbon nanotube tether is greatly impacted by the presence of carbon nanotube defects. Defects come in the form of nanoholes and nanocracks and involve the loss of one or more hexagonal rings. For reference, a space elevator would be comprised of 60% carbon nanotubes and 40% epoxy composite, but contain a mass of only 2% epoxy (Edwards 2000). The epoxy composite sections would have a minimum length of 100μm and be used to connect carbon nanotube segments of 4mm to form the cable. These carbon nanotube segments would consist of parallel and diagonal nanotubes compacted into a small volume to form an extremely strong layer. This design is meant to ensure that the failure of individual carbon nanotube does not affect the group and that defects do not increase in size, however, as mentioned by Pungo (Pungo 2013), even one small defect can have a large impact on the strength of carbon nanotubes. For example, the loss of just one hexagonal ring reduces the tensile strength of a [5,5] carbon nanotube from 105 GPa to 70 GPa and of a [10,10] carbon nanotube from 88 GPa to 56 GPa (Pungo 2013). Assuming the existence of defects larger than one hexagonal ring, the carbon nanotube cable of the space elevator is likely to only retain a strength of 30% that of a defect-free carbon nanotube cable. (Note that Edwards (Edwards 2000) references strength in context to a 0.34 nm thick layer of a single carbon nanotube segment in the cable and that a down scaled evaluation would result when considering the entire cable segment, depending upon the difference in cross sectional areas.) The strength remaining in the cable after accounting for defective nanotubes is less than 36 GPa, a value which is insignificant in comparison to the 63 GPa the cable must support in tension. This unavoidable loss in strength is why it will be a considerable number of years before a space elevator constructed from carbon nanotubes is possible.

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Conclusion and Alternatives

Carbon nanotubes have resurrected the idea of a space elevator. Compared to common materials, such as steel or Kevlar, the strength-density ratio of carbon nanotubes enables a miniscule taper ratio and mass in the cable required to support the elevator. Defects in carbon nanotubes lead to a 70% decrease in strength of the cable and render the project currently impossible. Research continues on the properties of carbon nanotubes, meaning that the material still has great potential. Alternatives to carbon nanotubes such as graphene and graphyne have been suggested for the construction of the cable. These allotropes consist of single monolayers of carbon opposed to a tubular shape. Graphene and graphyne are similar in strength to carbon nanotubes, but possess different physical properties, allowing the materials to be applied in many ways that carbon nanotubes cannot. No research addressing the application of graphene or graphyne to space elevators has been conducted in detail, however, because the different physical properties that the monolayers posses are not ideal for structuring a large cable. Nonetheless, like carbon nanotubes, graphene and graphyne are the materials of the future.

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