Building the Space Elevator Tether

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A simple Earth-based space elevator consists of a cable or tether extending from the surface to well beyond geosynchronous orbit. A climber grips the tether, pulling itself upward and delivering payload to space. For a space elevator to be feasible, the material from which the tether is built must be strong enough that the tether can support itself and any climbers that ascend it. Three such materials exist today and their industrial-scale production seems near at hand. These materials are compared and, based on previous studies, required improvements for each are listed. The material properties, along with the load, determine the shape and mass of the tether. Two example tether shapes are shown: one using the constant stress model and another which takes into account atmospheric winds and orbital debris. Options for tether construction are discussed. These are influenced by the material fabrication process, the way in which materials are combined and arranged in the tether and how much of the fabrication takes place on Earth or in space.

Keywords: Space Elevators, Strong Materials, Tether Construction

1 MATERIALS

The discovery of carbon nanotubes (CNT) [1] sparked renewed interest in the space elevator, resulting in studies which demonstrated its feasibility [2, 3]. The advent of two more strong materials, single crystal graphene (SCG) [4] and hexagonal boron nitride (hBN) [5], along with the realization that a space elevator climber could be built using existing or soon-to-be-developed technology [6], brought the space elevator into the realm of serious engineering consideration.

It now seems worthwhile to examine the available strong materials in terms of their usefulness in constructing the space elevator tether. While the strength of these materials is great enough to make space elevators possible, other material parameters are critical for efficient climbing and high cargo throughput. Some of these parameters may fall short of the requirements for a robust tether, requiring that the original strong material be augmented in some way, or that two or more such materials be used together.

The design of the tether depends not only on the material parameters, but also on the climber payload size, frequency of lift-off, debris avoidance and the number and mass of stations attached to the tether, to name a few. For simplicity, a single space elevator is considered, consisting of a single tether extending from Earth's surface to an altitude of 100,000 km, an active counterweight attached at the apex and several climbers. Proposals to build several such elevators located along the equator, with daily climber lift-offs, achieve a high mass throughput much superior to today's rocket launches [7].

The construction of the tether and its deployment will be closely linked. Whether the first tether is constructed on Earth and then sent to space for deployment, or deployed as it is constructed in space, is an open question. The answer will probably be determined by the requirements of the material manufacturing process and the orbital stability of the deployment process.

2 TETHER DESIGN INPUTS

The tether design and how it will be built depend on physical, engineering and economic considerations. Physical considerations include the dimensions and mass of the tether, its motions and its stresses, the climber mass, its velocity and available power, and debris avoidance. Engineering inputs include the type of climber and what it will carry, what, if any, stations will be attached to the tether, tether construction methods and the safety factor. Economic considerations will determine the mass throughput required for practicality and profitability. These include the frequency and reliability of climber lift-off and the desire to achieve regular operations at the earliest possible date.

2.1 Physical Parameters

The mass of the tether is determined by the maximum stress it can sustain. This is in turn determined by the mass and number of climbers and the tether material. The smallest tether mass for a given load is given by the constant stress model of Pearson [8]. In this model, the cross section of the tether varies with the intra-tether forces. The cross sectional area A as a function of the altitude x is given by:

$$A(x) = A(0)exp\{\frac{\rho}{\sigma}[\mu_e(\frac{1}{R_e} - \frac{1}{R_e + x}) - \frac{\Omega_e^2}{2}((R_e + x)^2 - R_e^2)]\} \quad (1)$$

where ρ and σ are the bulk density and equilibrium stress of the tether material and μ_e, Ω_e and R_e are the gravitational parameter, rotational velocity and equatorial radius of Earth, respectively. The ratio σ/ρ is the prime criterion for tether design. It is the specific strength of the material; the larger it is, the less material is required to build the tether.

The cross sectional area at Earth's surface, $A(0)$, is determined by the force on the climber at the surface,

$$\sigma A(0) = m_c[\frac{\mu_e}{R_e^2} - \Omega_e^2 R_e] \quad (2)$$

where m_c is the mass of the climber. An apex anchor can be added to shorten the length of the tether. For a length L, the anchor mass is given by:

$$\sigma A(L) = m_{AA}[\Omega_e^2(R_e + L) - \frac{\mu_e}{(R_e + L)^2}] \quad (3)$$

Choosing the material, climber mass and tether length, the tether shape and mass can be determined using Eqs. 1 and 2.

The climber velocity should be as high as possible, consistent with available power, stress in the tether and minimization of tether oscillations. Velocities between 200 and 300 km/hr seem reasonable. The Coriolis force, which is perpendicular to the climber direction of motion and proportional to its velocity, induces oscillations in the tether which must either be damped out or counteracted by other climbers. If the velocity is too high, this becomes more difficult. Higher velocities also produce more bending of the tether in the region of the climber; this could be a problem if the tether material is very stiff.

Debris avoidance and collision are manageable problems [9, 10], which may be mitigated in part by tether design. The tether can be made wider where debris is more frequent and a curved cross section could be used to reduce the chance of tether severance by a single projectile. Adding width to the tether is a departure from the constant stress profile of Eq. 1, but it is not essential that such a profile be used. Tether oscillations, timed to miss larger orbital objects, could also be induced. This assumes that the tether material has sufficient elasticity to sustain the oscillations.

2.2 Engineering Parameters

Several types of space elevator climber are envisioned; their drives can be categorized as electromagnetic or friction-based [6]. Friction-based drives are usually wheeled vehicles and depend on the mutual coefficient of friction between the wheels and the tether. Electromagnetic drives, such as magnetic levitation, depend on the conductivity of the tether. The type of climber chosen will depend on the choice of tether material.

It will be useful to have stations attached to the tether at various altitudes, say at low Earth orbit (LEO), geostationary Earth orbit (GEO) and the apex. Each station added above or below GEO would increase the required tether mass and would affect its tension and dynamics. In the simplest proposal, there would be a single station, the apex anchor, which fulfills the roles of counterweight, oscillation damper and spaceport.

When deciding on a value for the operational, or equilibrium, tether tension, a safety factor must be included. A factor of 1.4 to 1.5 is typical for aerospace applications [11]. The equilibrium tension would thus be the maximum material tension divided by 1.4, minus a bit more to be sure that the material is in its elastic range.

Tether construction includes the fabrication of the basic tether material, the assembly of the material into a tether of the desired mass and shape and the tether deployment. Each of these aspects is intertwined with one another and will be discussed in Section 5.

2.3 Economic Considerations

Space elevators have the potential to vastly out-perform rockets in terms of payload mass, lift-off cadence, reliability, safety and reduction of cargo bay restrictions. A desire to make space elevators operational at the earliest possible date means that they will likely be smaller, with tether masses in the one to a few kiloton range and climber masses ranging from 5 to 20 metric tons. These elevators will eventually be augmented in order to carry more mass with climbers as large as 100 tons. [12]. The first climbers will probably not carry people beyond LEO. Even at the highest envisioned climber speeds, any trip beyond that will mean days spent in the radiation belts. Shielding for this will significantly increase the climber mass, reducing its payload. Passenger travel will then require the larger climbers and therefore more massive tethers.

The payload mass of a single space elevator scales linearly with the tether mass and there is no physical limit to this mass, other than the availability and cost of the material. Of course, multiple space elevators will be used to increase throughput. One proposal for an early array uses six elevators grouped in three pairs, each pair equidistant from the other along the equator. [7]

3 MATERIALS

The three candidate materials, shown in Fig. 1, can be classified as one dimensional (CNT) or two dimensional (SCG and hBN). Dimensions in this context refers to the number of spatial dimensions in which a molecule can grow while still retaining the same characteristics. For example, carbon nanotubes can only grow from either end of the tube, provided it is not capped, and remain the same material. SCG and hBN can grow in the x and y dimensions, forming planar structures.

3.1 Comparison

Each material has been manufactured in several varieties in lengths up to 0.5 m [13, 14, 15]. To concentrate on the most likely candidates, one variety from each type was selected for comparison: graphene super-laminate (GSL) made from SCG, hBN and single-walled carbon nanotubes (SWCNT). Each has its strengths and weaknesses as shown in Table 1.

3.2 Carbon Nanotubes

Carbon nanotubes were the tether material of choice for space elevator designs between 1994 and 2006. They have potentially the greatest specific strength, (200 GPa)/(1,600 kg/m^3) = 1.25 × 10^8 N m/kg , of all the possible tether materials. However, the high value in Table 1 is a theoretical maximum which has never been measured. Tensile strengths in the range 77 to 100 are more likely. The coefficient of friction for SWCNTs is excellent, making them amenable to friction-based climber drives. Electrical conductivity is poor, 0.12% of that of copper. Information on the shear strength of SWCNTs is missing. In fact, such

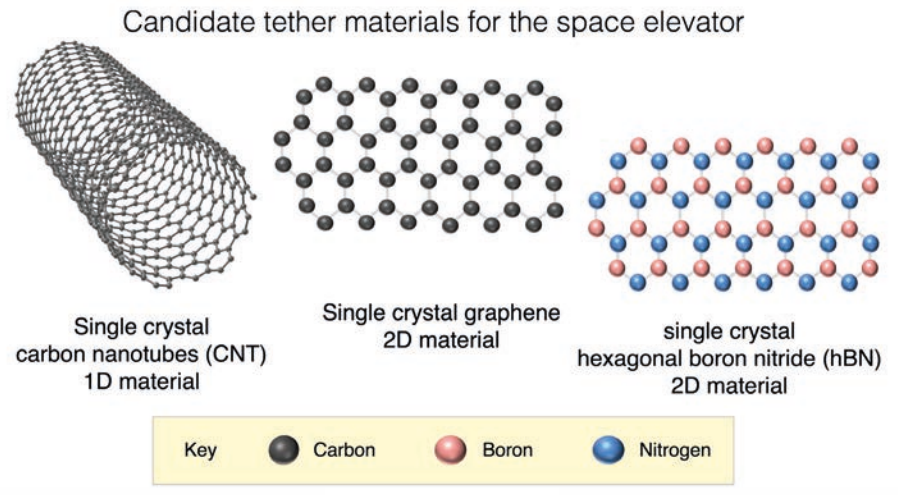

Fig.1 Molecular configuration of space elevator tether materials.

information may not be relevant to single strands of SWCNT, but only to weaves or braids of them which could make up the tether.

While research into CNTs is ongoing and robust, there has been little progress in demonstrating long single molecules of SWCNT after 2013. There are different varieties of SWCNTs with different properties and multi-wall CNTs which have still different properties. Any one of these may in the future be found to grow into long threads, but for now, 2D materials seem to have more promise as tether materials.

3.3 Graphene Super-laminate

Graphene super-laminate will be made from single-crystal graphene. A practical tether will require thousands of layers of atomically thin (0.335 nm) graphene. A particular stacking of these layers takes maximum advantage of the Van der Waals forces which draw them closer together and slightly increase the bulk density over that of SCG.

GSL has a high specific strength, (130 GPa)/(2,298 kg/m^3) = 5.66 × 10^7 N m/kg, 160 times greater than high-strength steels. The superior electrical conductivity of GSL makes it a prime tether candidate for climbers with electromagnetic drives. Its low coefficient of friction makes it problematic, but still usable, for friction-based climbers.

Another weakness of GSL is its low shear strength. Because of this, the force of climbers gripping the outer layers of the laminate will not all be transmitted to the inner layers and the outer layers may be stripped off. An estimated shear strength of more than 9 GPa [25] will be required to withstand the stress at the climber-tether interface.

The friction and shear strength can be improved by further processing of the GSL. Adsorption of hydrogen on SCG causes dimpling and will increase the coefficient of friction. The interlayer shear strength can be increased by cross-linking. High pressure conversion of the sp2 bonds between carbon atoms in a layer to sp3 bonds with atoms from adjacent layers will form strong cross-links. If these are close enough together, the shear strength can be increased sufficiently to resist stripping.

3.4 Hexagonal Boron Nitride

The specific strength of hBN, (100 GPa)/(2,200 kg/m^3) = 4.54 × 10^7 N m/kg, is about 20% less than that of GSL, but it is still competitive as a tether material. While GSL is a very good conductor, hBN is a very good insulator. Using hBN as the tether material, then, rules out the use of electromagnetic climber drives, but for friction drives, it is excellent.

The advantage of hBN lies in its higher coefficient of friction and greater resistance to shear forces. A greater coefficient of friction means that a climber will not have to exert the high compressive forces required with GSL. This in turn means a lower applied shear stress on the tether.

With its higher coefficient of friction and shear strength, hBN would require much less of the additional processing needed for GSL. Only the shear strength would need to be augmented, by a factor of perhaps 20 versus 100 for GSL. [25]

4 TETHER SHAPE

4.1 Rope or Ribbon?

The tether will likely take one of two cross sectional shapes:

TABLE 1: Comparison of selected properties for three tether materials

Property	GSL	hBN	SWCNT
Tensile strength (GPa)	70-130 [16]	100 [17]	77-200 [18]
Shear strength (GPa)	0.14 [19]	3.1-4.3 [20]	unknown
Coefficient of friction	0.03 [21]-0.1 [22]	0.23-0.27 [23]	0.22-0.24 [24]
Density (kg/m^3)	2,298 [25]	2,200 [26]	1,600 [27]
Elec. conductivity (S/m)	9.6 × 10^7 [28]	1.89 × 10^{-7} [29]	7.3 × 10^{-4} [30]

circular, in which the basic material is curled or braided into a rope, or a rectangle, in which the material is woven or laminated to form a ribbon. A large, flat surface will provide a better contact area to a climber, which will be needed regardless of the climber drive type. The strength of the proposed materials allows the tether to be very thin, making the ribbon design the most efficient use of mass for a given width.

A ribbon has an advantage over a rope in terms of debris mitigation: it can be made wider to increase the area presented to small orbital debris. While a rope presents a smaller cross section than a ribbon, it would take only one impact to sever it. A broad ribbon would survive more impacts as long as they have high angles of incidence. For low angles, one impact could slice the ribbon along its width. In this case, the ribbon cross section could be curved so that a single impact would make two small holes instead of one large one. [9]

4.2 WIDTH, THICKNESS AND MASS

Equations 1, 2 and 3 give the cross sectional area as a function of altitude. For a ribbon shape, the thickness of the tether can be held constant while the width varies with altitude. In that case, the width will vary like the shape in Eq. 1. Alternatively, the width could be constant with the thickness varying.

A few assumptions must be made in order to develop a specific cross section profile. To start, a 20,000 kg climber is placed at the base of the tether, that is, at the equatorial radius of the Earth. The tether will also be pre-tensioned at the base with a force of 147 kN, equivalent to adding another 15,000 kg to the climber. This is to take up tether slack when the climber is ascending. The tether material is taken to be GSL, which has the highest specific strength. The equilibrium stress is taken to be 60% of the maximum tensile strength: $\sigma = 0.6 \times 130 = 78$ GPa. This value is probably well within the proportional region of the material and includes a safety factor of 1.4. Now Eq. 2 can be used to determine the area $A(0)$ of the tether at its base: 4.38 mm^2. Using this value in Eq. 1 gives the width as a function of altitude, shown by the solid curve in Fig. 2.

For a tether of constant width 1 m, the thickness versus altitude can be read directly from Fig. 2, with μm units instead of mm^2. At the base it is 4.38 μm; at GEO it is 18.2 μm. If instead, the thickness is taken to be constant at 10 μm, the width varies from 0.438 m at the base to 1.82 m at GEO. A 10 μm thickness

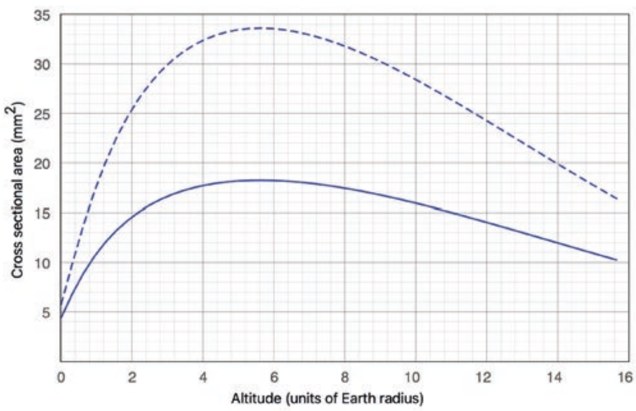

Fig.2 Cross sectional area of tether versus altitude for GSL (solid curve) and hBN (dashed curve). The total force at the base is due to a 20,000 kg climber with a 147 kN tether pre-tension.

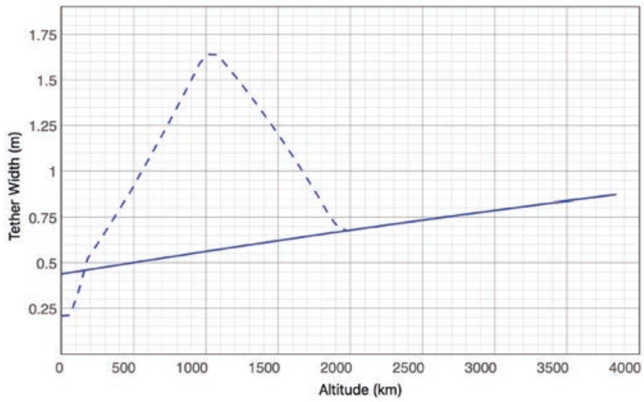

Fig.3 Tether width modified to reduce wind effects and increase survivability from small diameter space debris (dashed curve), compared to the unmodified, constant stress cross section (solid curve). The values at 0 and 60 km altitude (dashed curve) have been multiplied by 100 for visibility.

corresponds to 29,851 layers of GSL. For the above cross section profile and a tether length of 100,000 km, the mass of a GSL tether is 3,429 metric tonnes. Eq. 3 gives the mass of the apex anchor as 1,504 metric tons, bringing the total mass of the one-climber space elevator to 4,953 tonnes.

Repeating the above calculation for hBN, with an equilibrium stress of $\sigma = 0.6 \times 100 = 60$ GPa, yields the dashed curve in Fig. 2. The corresponding base area, counterweight mass and tether mass are 5.70 mm^2, 1,850 metric tonnes and 5,796 metric tonnes, respectively. The mass of the total system becomes 7,666 metric tonnes. The lower specific strength significantly increases the tether area at all altitudes and, since the bulk density of hBN is only slightly smaller than that of GSL, the total mass of the single-climber system.

A more practical system will have several climbers on the tether at any one time [31]. In order to support additional climbers and the stresses caused by climber motion, the mass of the tether must be increased beyond the values mentioned above. However, the additional mass does not scale linearly with the number of climbers; in fact, it is much less as the effective gravity decreases with altitude, becoming zero at GEO.

4.3 Modifications of the Tether Shape

The constant stress model is by no means required for a functioning space elevator; it is merely the most mass efficient. Issues such as debris collision, wind loading in the atmosphere and local thickening of the tether near splice joints (if any) all entail deviations from the constant stress shape which add mass. The first two issues are addressed in a possible modification of the above tether shape in which GSL is the assumed material.

The first 60 km of the tether will be buffeted by winds and so must present the smallest possible vertical area. The shape of the cross section in this case should be square or circular. For a square, using the base cross section from Fig. 2 of 4.38 mm^2, the width is 2.09 mm. The cross section changes slowly from 2.09 mm by 2.09 mm to 2.11 mm by 2.11 mm at an altitude of 60 km. From there, the cross section changes from a square to a thin rectangle 453 mm wide by 10 μm thick at 120 km altitude. Micrometeorites and space debris start to appear in this region. The density of space debris increases from 200 km to a peak at about 1,000 km and then decreases again. Keeping the width constant at 10 μm and increasing the width of the tether ribbon from 0.35 m at 120 km to 1.64 m at 1,020 km reflects this and substantially increases the tether's ability to survive small projectile impacts. This variation in width is shown by the dashed curve in Fig. 3. In order to compare this to the constant stress shape, the area plotted in Fig. 2 is assumed to come from a ribbon 10 μm thick at all altitudes. This is shown by the solid curve in Fig. 3.

Such modifications solve two problems and add a relatively small amount to the total mass of the tether. They do, however, pose difficulties for climber designs. The very small area of the tether below 60 km will make it hard for a climber to grip it and the climber will have to accommodate the large variation in tether width from Earth to GEO. Adding curvature to the tether will also cause difficulties for the design of the climber drive.

5 TETHER CONSTRUCTION

While a ribbon seems the most appropriate shape for the tether, there are many ways to make it. The simplest is to laminate thousands of 2D layers of GSL or hBN until sufficient strength is achieved. Alternatively, CNTs or even rolled-up GSL or hBN, could be woven into a flat fabric which could itself be laminated to make a ribbon.This option has an advantage of being less prone to corrosion in the atmosphere because the threads have no edges exposed to gases. It has the major disadvantage that any braid or weave is always weaker than its constituent threads.

Concentrating then on flat, 2D layers of GSL or hBN, how will they be made? Rapid fabrication is crucial; tens of thousands of layers, each with an area of roughly 10^8 m^2 will have to be manufactured in the span of several years. Currently, the fastest production of polycrystalline graphene is 100,000 m^2 per year [32]. In principle, single crystal graphene should not take longer, but it is clear that fabrication speeds will need to be greatly increased. Fortunately, there is no known upper limit on this speed, and plenty of room for innovation.

5.1 Hybrid Tether

For simpler construction, a tether of 100% hBN or GSL would be ideal. It is clear from Table 1, though, that neither material meets all the requirements by itself. GSL has a higher specific strength, but a lower coefficient of friction. hBN has greater shear strength and a bigger coefficient of friction, but a lower specific strength. Without the significant modification of either material, it seems that a hybrid of the two solves some problems. One possibility is to make the bulk of the tether from GSL, with its outer layers made of hBN. The GSL provides the strength and the hBN provides the friction. It has been demonstrated that hBN will naturally bond to GSL [33] which is a plus for the fabrication process.

5.2 Splicing

For maximum possible strength, each layer of material should be manufactured with the full length of the tether, or 100,000 km in this case. This could turn out to be impractical for several reasons: the shorter the GSL layer, the less likely it is to have defects; transporting long segments from the manufacturing site to the deployment site may be difficult; the tether deployment method may require shorter segments.

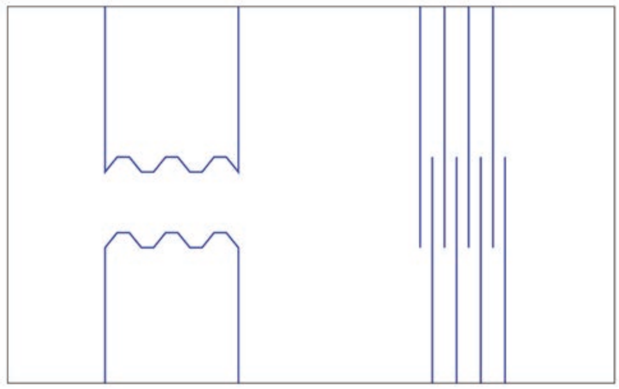

Fig.4 Left: view along the width dimension of two tether segment ends to be attached by completing the graphene matrix in the gap between them. Right: view along the thickness of interleaved lapping of graphene layers to form a splice.

There are several ways that tether segments might be connected. Each of them reduce the ultimate tensile strength of the tether, but some do not reduce it by very much.

One way is to fill in the graphene matrix between the two ends, effectively making a continuous crystal. The two ends would be precisely aligned and graphene deposited in the gap so as to complete the crystal structure. This is ideal and would cause no reduction in tether strength. It would be very difficult, though. The alignment would have to be perfect and the graphene deposition between the two ends would need to be of the same quality as in the production of the segments. It would also have to be done during deployment.

Another method is to use a lap joint. The laminations of one segment would be interleaved with those of the other segment, as shown in Fig. 4. The Van der Waals forces between the laminations provide the resistance to shear that is present in such joints. The longer the overlap region, the greater the tensile strength of the overall tether.

5.3 Fabrication and Deployment

Chemical vapor deposition (CVD) is the method currently used for graphene production. Depending on the particular type of CVD used, this process will involve temperatures between 300 K and 2,000 K to drive the chemical reactions and large vacuum chambers in order to prevent gases from adsorbing onto the graphene surface. Individual sheets of graphene would be laminated into GSL which would be collected onto spools for deployment.

The first several spools of material would be transported by rocket to near geosynchronous altitude, where some tether material would be payed out toward Earth and some at the same time in the opposite direction. Once the first pilot tether is established, additional laminations could be added to the tether by light-weight construction climbers [2].

It is important for the strength of the tether that no gasses are trapped between the laminations. This is only a problem for the part of the tether constructed in the atmosphere, where special precautions would be required. The stiffness of graphene is also a concern. While each layer is so thin that even a 100,000 km length could be rolled into a spool that would fit in the hold of a rocket, the Young's modulus of graphene is high, indicating that it could be quite stiff. It would then be difficult to wind it tightly onto spools. This would mean shorter tether segments which need to be spliced.

The orbital dynamics of this procedure are complex and still being studied [34]. While the motions and stability of a deployed space elevator are understood, tether deployment will be a delicate balance of mass flow, elasticity in the tether and Coriolis forces against the deep gravity well of Earth.

6 CONCLUSION

A suitable material for the construction of the space elevator tether appears to be near at hand. There are three materials to choose from, each of which has seen rapid development since their discoveries. It is essential that the sample size of these materials be increased so that detailed mechanical, electrical and thermal testing can be done.

Given what is known now, graphene super-laminate seems the best choice, with hexagonal boron nitride as an alternative. Methods of improving these materials to meet the demands of the tether have been proposed, but their details will depend on the outcome of material testing. The challenge with any of these materials will be the achievement of sufficiently high manufacturing speeds so that kilotons of tether can be produced in a reasonable time. However, the history of rate increases in graphene production are encouraging enough to think that the tether material will be ready when needed.

The shape and mass of the tether are well determined by the material parameters and the requirements of the regions in which the tether operates. A ribbon shape, flat and thin, meets the requirements of space elevator climbers, space debris mitigation and efficient distribution of mass. It the atmospheric section, a rope shape would reduce wind drag.

The method of tether deployment is still an open issue. Its orbital dynamics are more complicated than those of a completed space elevator, and any deployment procedure will have to incorporate the details of tether fabrication and delivery to space. Several options exist, but the construction of a small pilot tether, which is built up over time, is probably common to all such methods.

The construction of the first Earth-based space elevator tether presents many challenges, but based on reasonable extrapolations of present-day technology, they can be met. After the first tether is deployed, things will get easier. Like the track for the first transcontinental railroad, once the first space elevator is deployed, it can be used to build all subsequent elevators.

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