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Fate of a Broken Space Elevator

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Abstract.
We study the events that unfold if a space elevator breaks, focussing on the light weight carbon nanotube elevators proposed by Dr. Edwards. We find that no matter where the elevator breaks, the top fragment of the broken elevator is always permanently ejected from the Earth's gravity well. The bottom fragment falls back toward the Earth, wrapping around it if the fragment is sufficiently long. We study the reentry of the space elevator ribbon and find that due to the large surface to mass ratio, most of the ribbon survives reentry. Once decelerated, the ribbon falls slowly to the Earth and imposes a significant but probably not destructive force to objects on the ground. Finally, we see that as it falls, the elevator is an insignificant threat to satellites, but is a large risk to other space elevators. Ways of mitigating this risk are presented.

1. Introduction

A space elevator is a tensile structure that reaches from an anchor point on the surface of a planet out into space, held up by the centrifugal force from the planet's rotation. Since the idea was first proposed (Artsutanov 1960; Lvov 1967; Pearson 1975) it has been a source of inspiration for the dreamers among us. For the worriers, it is just another thing that can break and fall on our heads. These worries have been vividly depicted in science fiction work such as Kim Stanley Robinson's Red Mars (Robinson 1993) in which a massive martian space elevator falls to the ground with cataclysmic violence.

Fortunately, space elevators don't need to be as monolithic as the science fiction writers depict. Dr. Edwards brought the space elevator much closer to reality by proposing a the light-weight carbon nanotube concept (Edwards 2000a). The elevator he describes is a ribbon thinner than a sheet of paper, along which climber vehicles can ascend. With a ribbon this thin, there is too much drag for the cataclysmic reentry imagined by Robinson.

A few qualitative claims are made in Edwards (2000b) about the events that would follow a break in a space elevator. This paper aims to be a first cut at confirming or denying those claims, to see what really happens to a broken space elevator, and what damage may ensue. Throughout the paper we will be considering the simplest possible break scenario: a space elevator with no climbers on it is severed at one place along its length, creating an upper and a lower fragment.

1.1. The Simulator

Many of the results in this paper have been produced through numerical simulation of the space elevator dynamics. These simulations have been run using Dr. Edwards' standard parameters (Edwards 2000b): ribbon strength $\sigma = 130$ GPa, ribbon density $\rho = 1300$ kg/m^3, elevator length of 91000 km and Young's modulus of 1 TPa. The ribbon is tapered for uniform stress along its length.

The simulation is done in a reference frame that rotates with the Earth. The forward Euler integration method is used with a time step of 1 second. The elevator is modeled as a set of 100 masses and springs moving under the influence of gravity, centrifugal force and the Coriolis effect. The springs only produce a force in tension so the ribbon cannot bear any compressive stresses. Springs break permanently when they are stretched beyond the breaking point of the ribbon material. Heavy longitudinal damping is added by placing dampers in parallel with the springs; this prevents large longitudinal oscillations from arising when the discrete masses that make up the elevator hit the Earth. Masses that enter the Earth are moved to the surface of the Earth and a friction force with a characteristic time of 10 seconds is applied to them.

1.2. Outline

The canonical way for a space elevator to break is for it to be severed at some point along its height. This produces two fragments. In Section 2. we see that the top fragment is completely lost when a break occurs. The next few sections consider the fate of the bottom fragment. Section 3. models the ribbon's reentry to determine whether it burns up or not. Then section 4. shows simulations of the bottom fragment falling back to Earth. The ribbon fragments that survive reentry fall to the ground, and Section 5. considers the possibility of damage due to these fragments. Finally, Section 6. looks at the risk of collisions between a broken elevator and satellites or other elevators.

2. The Upper Fragment

The currently accepted scenario for what happens when a space elevator breaks is in citet[Sec. 10.9]edwardsNIAC. For a break near the bottom of the elevator, the upper fragment will "float" upward and drift slightly westward due to Coriolis forces. Tidal forces keep the fragment vertical, and it ends up in a relatively low orbit orbit around the Earth. A recovery mission could recapture the bottom of the fragment and reattach it to the anchor point.

As we shall see in this section, this scenario is completely inaccurate. We first show this using simulation. Then, we point previous work that confirms the simulation results.

2.1. Simulation Results

Figures 1(a) and 1(b) show the result of a simulation of a space elevator with no climbers breaking near its base. They differ widely from the previously accepted scenario (Edwards 2000b, Sec. 10.9). After the break, the base of the elevator springs upward at a velocity around 1.1 km/s. As expected, the elevator quickly starts to drift westward. The tidal forces are not strong enough to keep the elevator vertical as it drifts westward, so it ends up spinning end over end. The elevator never does end up in a stable orbit, it steadily moves away from the Earth on a roughly hyperbolic orbit (that looks like a spiral because of the rotating reference frame). Recapturing and reattaching looks like a very unlikely prospect.

If climbers are present on the ribbon. The events that follow the break are slightly less fast. In Figure 1(c) we show what happens if a climber is attached to the base of the elevator fragment. The climber mass is selected to be slightly less than the mass needed to equilibrate the fragment. The initial rise of the ribbon is slowed down somewhat in this case, but the subsequent events are effectively indistinguishable from those when no climber is present. The fragment still ends up completely escaping from the Earth. This experiment suggests that there aren't any climber tricks that could be played to prevent the upper fragment from escaping after a break.

We have also simulated breaks higher along the elevator. The top fragment of the elevator escapes even faster in these cases as there is less mass deep in the Earth's gravity well holding it back.

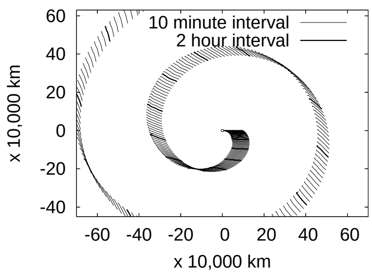
Overall, it appears that once the elevator is severed, its upper fragment is completely lost. The best strategy seems to be to avoid the break altogether. Since the most vulnerable part of the elevator is near the ground, having multiple redundant ribbons at the base of the elevator could be an effective strategy to reduce the risk of having a complete break.

2.2. Instability of Long Tethered Systems

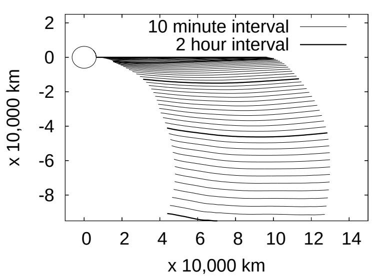
The results of our simulation can be related with a relatively old result on dumbbell tether systems. If the distance between the ends of the dumbbell is increased sufficiently, the system ends up having a positive orbital energy and does not have a stable orbit (Lorenzini and Arnold 1985; Arnold 1987; Carroll 1985). Here, we are seeing the same phenomenon in the case of the space elevator.

When there are no climbers, the configuration after the break is not an equilibrium configuration, the elevator is accelerated upward, and has enough energy to escape from the Earth. When a climber at is placed at the base of the elevator, the situation just after the break is an equilibrium configuration, but as in the dumbbell case it is unstable.

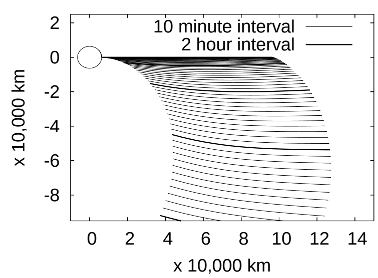
The case of an sky-hook, a space elevator that is not attached at its base has also been studied in detail (Steindl and Troger 2005). It is equivalent to the broken space elevator with a climber at its base. That work confirms that this configuration is unstable. To get rid of the instability, they propose to add a large mass (such as a space station) at geosynchronous altitude. This large mass makes a negative contribution to the orbital energy of the system, allowing it to become stable. Another possibility would be to shorten the elevator until it no longer has enough energy to escape from the Earth. However, as we shall see is Section 6., having the top fragment leave the Earth is actually a boon as it avoids collisions with other orbiting objects.



(a) No climbers, long term



(b) No climbers, short term



(c) Climber at base, short term

Figure 1. Space Elevator breaking near its base, as seen from above the North pole. The position of the elevator is shown at regular intervals in a reference frame rotating with the Earth.

3. Reentry

We now turn our attention to the bottom fragment of the elevator, the one which falls back to Earth. According to Edwards (2000b, Sec. 10.9), all the bottom fragment beyond a certain height burns up during reentry. This occurs as soon as the kinetic energy is sufficient to raise the ribbon temperature beyond its ablation point. In this section we model the reentry process taking into account black body radiation from the ribbon and find an approximate velocity beyond which the ribbon burns up on reentry. Unfortunately, there is not enough detail in Edwards (2000b) to allow precise numerical comparison with our result.

The analysis we present is largely drawn from Jones and Kaiser (1966), which deals with the ablation of meteoroids entering Earth's atmosphere. The only difference with this work is the geometry of the ribbon and the velocity range that is being considered.

We assume that the ribbon is made up of carbon nanotube threads about 10 μm in diameter, and that these threads are widely spaced out. If the threads are not spaced out then a bit less black body radiation will occur.

3.1. Forces Acting on the Ribbon

The ribbon's motion is guided by three main forces: gravity, ribbon tension and friction with the atmosphere. Since the ribbon is essentially wrapping itself around the Earth as it falls, we will consider that the ribbon is horizontal as it reenters the Earth's atmosphere, and that its motion is vertical.

We begin by expressing the forces acting on a piece of ribbon with length $\mathrm{d}l$ and cross-section A. For a density ρ, the mass of this length of ribbon is

$$\mathrm{d}m = \rho A \mathrm{d}l. \tag{1}$$

Gravity. Newton's law of gravitation tells us the acceleration of the ribbon due to gravity

$$a_\mathrm{g} = -\frac{GM\mathrm{e}}{r^2}, \tag{2}$$

where $M\mathrm{e}$ is the mass of the Earth, G is the gravitational constant, and r is the distance to the center of the Earth. During reentry, we are within about 100 km of the surface of the Earth, so $a_\mathrm{g} \approx g = 9.8$ m/s^2.

Curvature. Since we are only considering up-down motion of a horizontal ribbon, the effect of the tension in the ribbon will be to accelerate the ribbon in the direction of its curvature with a force

$$F_\mathrm{c} = \sigma A \frac{\mathrm{d}l}{r_\mathrm{c}}, \tag{3}$$

where σA is the tension in the ribbon and r_c is the radius of curvature of the ribbon.

Dividing by (1) gives the acceleration of the ribbon due to curvature

$$a_\mathrm{c} = \frac{\sigma}{\rho r_\mathrm{c}}. \tag{4}$$

To evaluate an order of magnitude for a_c, we take $r_c = -re$, i.e., the ribbon has the same curvature as the Earth. When the tension in the ribbon reaches the breaking point of 130 GPa, this gives an acceleration of $a_c \approx 1.6g = 15.7$ m/s^2.

Atmospheric Friction. If the atmosphere has density ρ_a then the ribbon intersects a volume $A_f v \rho_a$ per unit time, where A_f is the area with which the ribbon is sweeping into the atmosphere. This gives a force

$$F_f = \Gamma A_f v^2 \rho_a. \tag{5}$$

where Γ is the drag coefficient, which should be close to unity in the regime we are considering.

The value of A_f depends on the geometry of the ribbon. To evaluate it, we introduce a parameter f_f, such that $A_f d = f_f A dl$, where d is the thickness of the ribbon. For a ribbon made of sufficiently spaced out threads of diameter d, $f_f = 4/\pi$. Dividing (5) by (1) yields the acceleration of the ribbon due to friction with the atmosphere

$$a_f = \frac{\Gamma f_f v^2 \rho_a}{\rho d}. \tag{6}$$

3.2. Deceleration Profile

The atmospheric density has a roughly exponential dependence on altitude $\rho_a = \rho_{a0} \exp(-h/H)$, where we will take $H \approx 7$ km as in Jones and Kaiser (1966). Considering that velocities of 1 km/s or more will be typical for reentry, the friction force will go from negligible to dominant within a few seconds only. Therefore, we will consider that the ribbon behaves upon reentry in the following way:

1. The ribbon is freely falling under the influence of tension and gravity only.
2. The atmospheric density suddenly builds up and the ribbon rapidly decelerates, under the influence of friction only, from a velocity v_∞ to a velocity close to zero.
3. The slowed ribbon falls to the Earth at its terminal velocity under the influence of all three forces.

The deceleration phase is the critical phase of reentry as it involves heat production, and possibly ablation of the ribbon. During this phase, the motion of the ribbon is approximately described by $\dot{v} = -a_f$. Noting that $v = -\dot{h}$, and using (6) we get

$$\frac{\dot{v}}{v} = \frac{\Gamma f_f \dot{h} \rho_{a0} \exp(-h/H)}{\rho d}, \tag{7}$$

which can be integrated to

$$v = v_\infty \exp\left(-\frac{\Gamma f_f H \rho_a}{\rho d}\right). \tag{8}$$

3.3. Heat Transfer

The main question we wish to answer is whether the ribbon will survive the heat produced during reentry. Some thermal modeling is therefore required. Because of the small size of the ribbon threads, we will assume that their temperature is uniform. We will then find the equilibrium temperature between frictional heating and black body radiation. We shall ignore heat capacity, which leads to a conservative approximation.

Frictional Heating. The heat produced by the friction force per unit ribbon mass is va_{f}. Approximately half of this heat is transferred to the ribbon:

$$Q_{\mathrm{f}} = \frac{1}{2}\frac{\Lambda f_{\mathrm{f}} v^3 \rho_{\mathrm{a}}}{\rho d}, \tag{9}$$

where $\Lambda \approx 1$ takes into account Γ and the exact proportion of the heat transferred to the ribbon.

Black body Radiation. As the ribbon heats, it begins to radiate heat. It radiates over an area A_{r}. We introduce the geometric parameter f_{r} defined such that $A_{\mathrm{r}} d = f_{\mathrm{r}} A dl$. For a ribbon made up of well spaced out threads, $f_{\mathrm{r}} = 4$. With this notation, the heat radiated into the ribbon per unit mass is

$$Q_{\mathrm{r}} = \frac{A_{\mathrm{r}}}{\mathrm{d}m}\epsilon\sigma \mathrm{B}\left(T^4 - T_{\mathrm{a}}^4\right) = \frac{f_{\mathrm{r}}\epsilon\sigma\mathrm{B}}{\rho d}\left(T^4 - T_{\mathrm{a}}^4\right), \tag{10}$$

where T and T_{a} are the ribbon temperature and the ambient temperature, and ϵ is the emissivity of the ribbon.

3.4. Maximum No-Burn Velocity

To evaluate the ribbon's temperature during its descent, we consider that frictional heating and black body radiation are equal, i.e., $Q_{\mathrm{r}} = Q_{\mathrm{f}}$. This yields the ribbon temperature

$$T^4 = T_{\mathrm{a}}^4 + \frac{\Lambda f_{\mathrm{f}} v^3 \rho_{\mathrm{a}}}{f_{\mathrm{r}}\epsilon\sigma\mathrm{B}}. \tag{11}$$

This equation reaches its maximum value when $v^3\rho_{\mathrm{a}}$ reaches its maximum value. Using (8) and differentiating tells us that the maximum temperature is reached when

$$\rho_{\mathrm{a}} = \frac{\rho d}{3\Gamma f_{\mathrm{f}} H}. \tag{12}$$

For *Gamma* $= 1$, $f_{\mathrm{f}} = 4/\pi$, $\rho = 1300$ kg/m^3 and d $= 10$ μm, the maximum temperature is reached at an atmospheric density of $\rho_{\mathrm{a}} = 4.9 \cdot 10^{-7}$ kg/m^3, compared with about 1.1 kg/m^3 at sea level.

The maximum temperature is then

$$T_{\mathrm{max}}^4 = T_{\mathrm{a}}^4 + \frac{\Lambda v_\infty^3 \rho d}{6 e f_{\mathrm{r}}\epsilon\sigma\mathrm{B}\Gamma H}. \tag{13}$$

This equation can be used to determine the velocity at which the ribbon begins to burn during reentry. Because the velocity and temperature appear as a third and fourth powers, changing the other parameters only makes small changes to the maximum no-burn reentry velocity. On the other hand, the maximum velocity does strongly depend on the ablation temperature of the ribbon material. For *epsilon* $= .5$, $\Lambda = 1$, $T_{\mathrm{a}} = 200\mathrm{K}$ and $T_{\max} = 600\mathrm{K}$, we get $v_\infty = 5.0$ km/s.

4. Simulations of the Bottom Fragment

We are now ready to simulate what happens to the bottom fragment after a break. Figure 2 shows it falling back to Earth for elevators severed at different positions along their length. In these simulations, reentry has been taken into account by breaking the ribbon if it reenters at a velocity greater than 5 km/s.

Initially, the fragment falls straight down. Then as it picks up speed, the Coriolis effect begins to deflect it eastward. For low breaks, the elevator entirely falls to the ground before the deflection gets very large, and it all falls very near the anchor. The highest portions fall fast enough to burn up on reentry, potentially releasing carbon nanotubes into the atmosphere.

For higher breaks, the eastward velocity builds up. The ribbon laying on the ground gets pulled taut, and the ribbon starts to wrap around the Earth as described in Red Mars (Robinson 1993). As the elevator wraps around the Earth, centrifugal force slows its fall, keeping the reentry velocity low enough for the ribbon to survive. The free end of the ribbon swings about as it falls, usually with enough force to cause the ribbon to break; a small fragment from the top is flung away from the Earth never to return. The remaining fragment, no longer being held up, falls down fast, usually burning up. Occasionally, as the ribbon gets severed during reentry the top fragment is able to escape from the Earth.

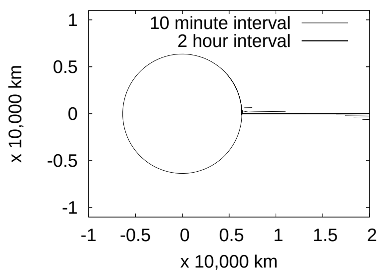
The details of what happen depend a lot on the friction that is applied at the surface of the Earth, and the discretization of the ribbon. However, the general trends described here seem to hold regardless of the exact parameters.

Overall, only a small fraction of the ribbon ever burns up. The worst case is Figure 2(c) where about half the ribbon below the break burns up. The amount of burning depends strongly on the maximum no-burn reentry velocity. Much of the elevator appears to reenter around 3 km/s, so if the limit velocity were much lower a lot more of the ribbon would burn upon reentry. If burning is ignored then no part of the elevator reenters above 10 km/s, so if the limit velocity were higher than that, the whole ribbon would survive reentry.

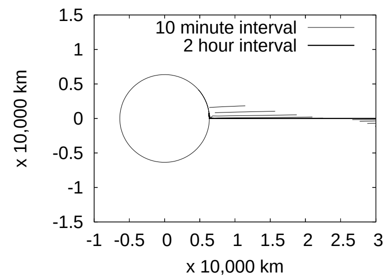
5. Damage on the Ground

5.1. Terminal Velocity

Once the ribbon has slowed, it falls to Earth under the combined influence of gravity and curvature pulling it downward, and friction slowing it. During this phase, the ribbon is moving slowly, and is hardly accelerating, so we consider that $a_{\mathrm{c}} + a_{\mathrm{g}} + a_{\mathrm{f}} = 0$. Effectively we are computing the terminal velocity of the



(a) 10%



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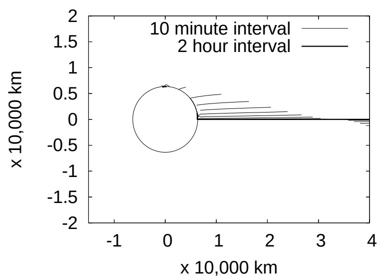
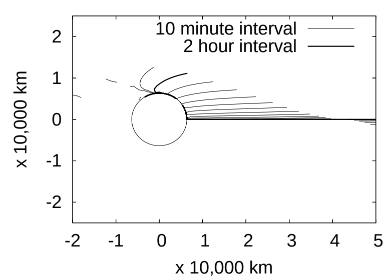
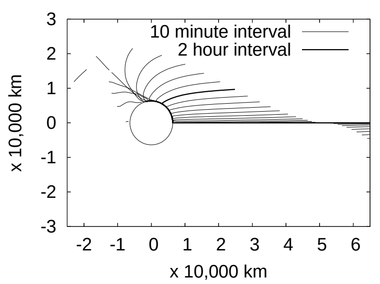


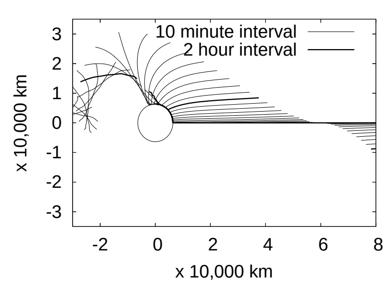
(c) 30%



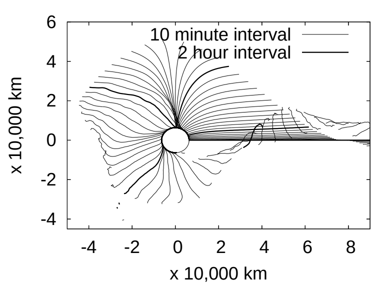
(d) 40%



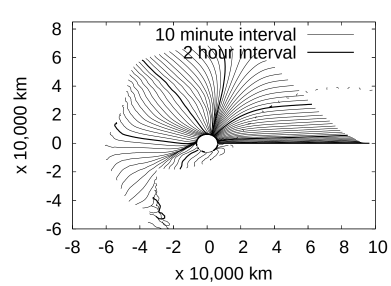
(e) 50%



(f) 60%



(g) 80%



(h) 100%

Figure 2. Space elevators falling back to Earth after being severed at different heights, seen from above the North pole.

ribbon. Using (6), we get

$$v_{\mathrm{term}}^2 = \frac{|a_{\mathrm{c}} + a_{\mathrm{g}}|\rho d}{\Gamma f_{\mathrm{f}} \rho_{\mathrm{a}}}. \tag{14}$$

At the surface of the Earth, $\rho_{\mathrm{a}} \approx 1.2\mathrm{kg/m^3}$, so $v_{\mathrm{term}} \approx 0.47\mathrm{m/s}$. With increasing altitude, v_{term} is proportional to $\exp\left(\frac{h}{2H}\right)$. Below about 43 km, v_{term} is below 10 m/s. This confirms what was stated in Edwards (2000b, Sec. 10.9): the ribbon will reach the ground at a very low velocity, and there will be no impact damage due to the ribbon falling.

5.2. Force on Ground Objects

Once the ribbon is on the ground, it can still be under a lot of tension, especially while higher portions are still wrapping around the Earth. Because of the Earth's curvature, this will translate into a downward force on the ribbon. If the Earth had a perfectly smooth surface, this force would be evenly spread along the length of the ribbon. In reality, however, the force will be concentrated on the objects that protrude from the ground, as in Figure 3. What kind of damage can that force cause?

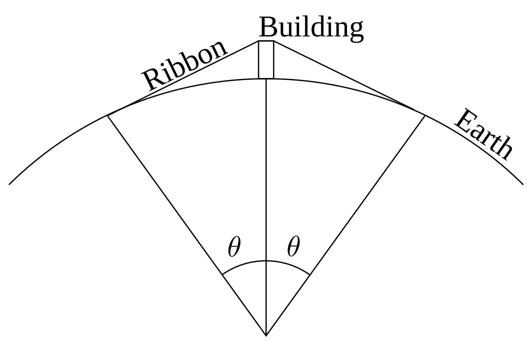


Figure 3. Once on the ground, the ribbon pushes down on objects that protrude along its path.

To evaluate this force, we need to determine the angular deflection of the ribbon at the protrusion. The worst case is when there is no other protrusion before the horizon. If the height of the protrusion is h, then the angle θ to the horizon is

$$\theta = \sqrt{\frac{2h}{R_{\mathrm{e}}}}. \tag{15}$$

The resulting force on a point above the earth is

$$F = 2\theta T = \sqrt{\frac{8h}{R_{\mathrm{e}}}} T. \tag{16}$$

For a 20 T elevator, with a breaking point of 130 GPa, the maximum tension that can be achieved anywhere along the ribbon before it breaks is 1 MN. The corresponding force is 1.1 kN (about 110 kg) at 1 m of height, ten times more at 100 m of height. A building (100 m) should be undisturbed by this force, and a person (1 m) may be trapped, but should not be hurt. Antennas or other fragile structures may be damaged.

For a ribbon made of n threads, each with diameter d, the cross-section of the ribbon relates the number of threads to the tension:

$$n\frac{\pi}{4}d^2 = A = \frac{T}{\sigma}. \tag{17}$$

Thus the force F will be spread across the effective width of the ribbon

$$W = nd = \frac{4T}{\pi d\sigma}. \tag{18}$$

The resulting force per unit width created by the ribbon is

$$\frac{T}{W} = \pi d\sigma\sqrt{\frac{h}{2R_\mathrm{e}}}. \tag{19}$$

For a ribbon stretched to the breaking point with 10 μm threads, the force per unit width is 1 kN/m at 1 m from the ground, or 10 kN/m at 100 m from the ground. This is comparable to the linear force on the blades of an ice skate, and is unlikely to cause significant damage. However, this calculation assumes that the ribbon lies flat on the ground. If it is all clumped together the linear force could be much greater and cause damage.

6. Collisions in Space

Up to now, we have wondered about whether the top fragment of the elevator is recoverable, and about the risks the bottom fragment represents for assets on the Earth. We now briefly discuss the possibility of a broken elevator damaging assets in space, namely satellites or other space elevators. In this section we shall assume that collisions are a bad thing, without going into the details of the damage that could ensue from a collision.

The good news is that the risk that is posed by the space elevator is over a short period of time only. The top fragment permanently clears geosynchronous altitude within a few hours after the break. The bottom fragment falls back to the Earth in less than 24 hours in the worst case. It is possible that the bottom fragment may break up leading to sections of tether that stay in orbit for longer periods of time. This case has never come up in the simulations, so it is at least somewhat unlikely. We shall therefore consider that there is a 24 hour period in which collisions can occur with the falling space elevator.

During this time, the elevator cannot be controlled by moving the anchor platform, as tension is lost at the platform as soon as the break occurs, and we shall assume that the ribbon falls too fast for the anchor to reel in the slack. Some minimal control may be possible using climbers or thrusters placed along the length of the ribbon, but we shall ignore that possibility here.

6.1. Risk for Satellites

The risk for satellites is very small. We recall (Edwards 2000b, Table 10.3.1) that it takes on average 5.8 days for an object larger than 1 cm to approach the unbroken elevator to within 10 m. Extrapolating loosely on this data, it seems that in all likelihood, the elevator has a small chance of encountering one object during its fall. Of the $\sim 100,000$ objects larger than 1 cm in orbit, only ~ 1000 are active satellites. So the chances of a satellite being hit as the space elevator falls can be estimated at well below 1%.

6.2. Risk for Elevators

It has been proposed (Edwards 2000b, chapt. 11 and 12) that the first mission of the space elevator once it has been deployed should be to build a second space elevator, so that cheap access to space is not lost if one elevator is destroyed. The potential worry with this strategy is that with multiple elevators present, if one elevator breaks, it may collide with other elevators and bring them down as well. Thus we need to wonder what the risk of elevators taking each other down is, and whether multiple elevators are in fact safer than a single one.

The possibility of a falling elevator taking other elevators down is much greater than the possibility of it hitting a satellite, for the same reason that it is much easier for two swords to hit than for a sword to hit a fly. If a satellite is in an equatorial orbit to within $1°$ then it is within a 110 km band on each side of the equator. If the base of the elevator is also within a 100 km band around the equator then for a 10 m satellite there is a one in 20,000 chance that the two will collide in any given orbit of the satellite around the Earth. If we replace the satellite with a ribbon fragment 10,000 km long that is tilted relative to a space elevator to within $1°$, then the space elevator fragment looks like an obstacle $10,000 \times \sin(1°) \approx 175\,\text{km}$ wide. A collision now seems quite likely. Fortunately there are ways to mitigate this risk:

1. Only deploy a single space elevator. Use it to lift a complete rolled up back up elevator into orbit, but only deploy the backup if the primary elevator breaks. This way the backup elevator is not vulnerable. This strategy may be good for the first space elevator, but at some point it will probably become desirable to have more than one elevator deployed at a time.

2. We see from Figure 1 that the base of the broken elevator is at an altitude greater than the length of the elevator before the elevator reaches a longitude $90°$ West of the anchor location. Thus for four elevators evenly spaced out in longitude, there is no risk from the upper fragment of a broken elevator.

   Because most space debris is in low Earth orbit, it is likely that in the event of a break, the break will be very low along the elevator. The elevators are sufficiently spaced out not to be at risk from either fragment. In fact Figure 2 suggests that the bottom part is not a concern as long as the break is below about 30,000 km.

3. If more than four elevators are desired, then fragments of a broken elevator will come close to unbroken elevators. The risk of a collision can be

mitigated by moving off the equator a few hundred kilometers (Gassend 2004). If it breaks, a non-equatorial elevator will fall toward the equator. Therefore, if all the elevators are off the equator by the same amount, the broken elevator will initially move out of the way of the other elevators, have crashed or escaped before returning to its initial latitude. On the other hand, if some elevators are farther off the equator than others, the ones that are nearest to the equator are at risk from the ones that are farther off. More work is needed to study the trajectories of non-equatorial elevators in detail, to better understand the limitations of this method.

In any case, the unbroken elevators are still attached to their anchor platforms, and can therefore be moved around to minimize the risk of collisions. The motion can simply be a move away from the equatorial region, or it can be adaptively chosen after observing the trajectory of the broken elevator.

Conclusion

The use of simulation and analysis has given us a better understanding of the events that follow a break in a space elevator. The top fragment of the elevator leaves the vicinity of the Earth within a few hours never to return. The bottom fragment falls back to Earth, wrapping around it if the break is sufficiently high.

The large surface to mass ratio of the ribbon allows the ribbon to survive reentry intact along most of its length. Usually only the end of the lower fragment ends up burning. After an intense deceleration phase the ribbon falls slowly to the ground at less than 1 m/s. Once it is on the ground, if the ribbon is still in tension, it can apply a significant force to objects protruding from the ground, but the force does not appear large enough to cause major damage.

Within the few hours during which they are sweeping space in the vicinity of the Earth, the elevator fragments pose very little threat to satellites, but can be a danger to other space elevators. Strategies to mitigate this risk have been proposed.

The sequence of events that are described in this paper differ substantially from what has been envisioned in previous work. In particular, recovering a broken elevator seems implausible. However, the previous conclusion that a break in the elevator is only catastrophic for the elevator itself has been confirmed.

This paper provides a first cut approach to the problem of broken space elevators. Many avenues for research remain open, such as modeling of North-South motions of the elevator fragments (especially after being perturbed by the atmosphere), refining the models for the ribbon interacting with the atmosphere, or looking more closely at the effect of climbers on the ribbon.

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