Space Elevators
A Study in Cable Design and More

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Abstract

Conventional rocketry faces many limitations. Infrequent launches, pollutants dispersing in the atmosphere, and the high cost of launches all make more developed access to space difficult. A space elevator can solve these problems with a unique payload delivery system. Simply put, a space elevator is a long cable that can stretch from the surface of the Earth out into space. Climbers can ascend this extraordinarily strong cable for a variety of purposes. This study has calculated the dimensions and structure of the entire elevator. One of the key objectives in this paper is to determine a tether design constructed of newly-developed carbon nanotubes and epoxy that combines strength, efficiency and adaptability in the relatively unfriendly environments of space. Furthermore, this study has examined and proposed solutions to many of the common issues associated with the space elevator concept. Lastly, this paper encourages further investigation in the development and mass production of carbon nanotubes, as well as the economic feasibility of space elevators in the near future.

1. Introduction

1.1 Goals

This study aims to analyze the feasibility of building a space elevator by utilizing technology that is currently available. As of today, the space elevator proposal has remained entirely theoretical. In fact, the basic design has advanced little since its initial formal proposal in 2000 [1]. This is largely a result of the lack of materials to construct a real space elevator. The space elevator design hinges on the ability of its tether to support itself over tens of thousands of kilometers in Earth's orbit, but as of yet there exist few materials capable of realistically fulfilling this requirement. Theoretically, the tether can be made of any material, but as the tether's altitude increases, it would have to widen substantially to support its own weight. As such, most studies on space elevators focus on technologies that might exist decades in the future. This study, however, will address the matter of cable construction using materials available to engineers today. In order to accomplish this, various cable configurations have been modeled in SolidWorks, a computer aided design software, to test their ability to handle stress. In addition, this research seeks to provide solutions to other issues associated with the elevator, such as climber propulsion and cable deployment.

1.2 Reasons for a Space Elevator

Everything that can be done with rockets can be done cheaper and with larger payloads using a space elevator [1]. Additionally, many missions that cannot be accomplished with rocket launches will become possible with the use of space elevators. The environmental impacts of launching rockets, including the fuel burned and the engines falling back to Earth, will disappear since space elevators can easily transport cargo and humans without major environmental concerns. Space-based solar panels can provide cheap, clean power to Earth's surface. An increase in communications and research will arise due to the plethora of new satellites that can be launched from the elevator. In addition, space elevators will allow for relatively easy disposal of dangerous nuclear or toxic waste in the isolated vacuum of space. Moreover, the space elevator can lead to a realistic solution to space debris, a growing problem which poses a serious danger of collision for satellites and interference for future excursions into space.

2. Background

2.1 Challenges with Elevator Design

The greatest challenge of building a space elevator is the construction of the long cable required to support the climbers. There are few materials that offer even a possibility for practical use. Furthermore, a power system must be developed that will enable long-distance transfer of energy to the climbers. The deployment of the elevator will be a delicate procedure as well. Other complications include weather, atomic oxygen corrosion, space debris, satellites, radiation, and political regulation [1].

2.2 Assumptions

For the purposes of this study, it is assumed that cable materials can be replicated on a large scale with the same length and strength as have been produced in laboratories. This paper does not assume the existence of any properties that have not been experimentally observed. Furthermore, a suitable epoxy for cable construction is assumed to exist and able to be mass produced.

2.3 Relevant Physics

The space elevator remains vertical through a centrifugal "force" that appears to act outwards on the cable. In reality, this force is simply an observation resulting from the inertia of a system. As an object swings in a circular motion, its velocity is perpendicular to its acceleration, which is towards the body that it travels around. In this type of motion, the "string" that connects the object in motion to the center of the circle it forms remains taut due to the inertia resulting from the moving object's velocity. This is the concept behind the space elevator. By anchoring a base point on the equator of Earth, where the tangential velocity on the surface will be the fastest, the cable that connects the top of the space elevator to the Earth will remain taut due to its high tangential speed. However, to overcome Earth's gravitational pull, the centrifugal force must be greater than the gravitational pull on the elevator. This occurs at an altitude of 35,786 kilometers, also known as geosynchronous orbit (GEO).

Therefore, the center of mass of the elevator must be over 35,786 kilometers above the surface of the earth. To minimize the amount of cable required, a counterweight at the end of the space elevator is necessary to pull the center of mass up above GEO and keep the elevator from collapsing back into Earth. Nevertheless, the ribbon must be able to support the tension from both below and above [2]. Recent discoveries of new nanomaterials allow for the strength required.

During deployment, the angular momentum of the spacecraft will be conserved if no external torque is applied, as the spacecraft rotates once per orbital period. As the craft extends the cable, its moment of inertia changes, slowing its rotation and eventually causing a catastrophic failure. This mechanism must be taken into account.

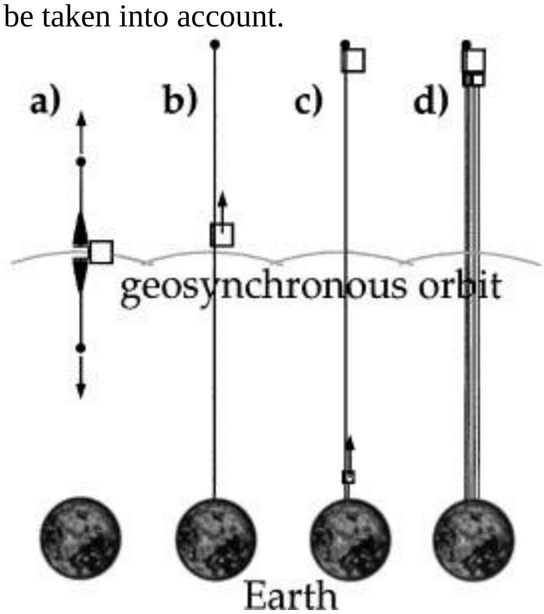

Figure 1: Earth and space elevator combination showing increasing cable thickness [3]

3. Software

SolidWorks was utilized to create 3D models of cable designs, as well as a scale model of the Earth-space elevator system. This program is a computer aided design tool that allows users to create and simulate 3D objects. Moreover, tensile forces can be measured using the simulation feature of SolidWorks and stresses on various points in the cable design were studied to determine the best design for a space elevator. Despite the fact that the properties of carbon nanotubes are not programmed into the software, a custom material was configured in SolidWorks that emulated the properties of carbon nanotubes. This custom material was used to test various cable designs. However, SolidWorks was not designed to handle a structure of this magnitude and designs could not be modeled to the desired specifications. Whereas thousands of tubes might be present in a cross-section of a real cable, only a few dozen could be mapped in the program. In addition, weaves, which utilize semi-unstressed nanotubes, were impossible to simulate accurately. Unfortunately, this resulted in quantitative inconsistencies between designs. Nevertheless, invaluable qualitative information was gained.

4. Cable Design

4.1 Material

The material used in a space elevator is the most important aspect of the project. For a long time, progress could not be made in the field due to a lack of appropriate materials. Even steel and Kevlar could not be applied to the construction of a cable due to the required taper ratio, the relationship between the width of the cable at geosynchronous orbit and the width of the cable at the base point on Earth. For most materials, the specific strength, or strength to weight ratio, is too low; the increase in width that will be needed as the cable supports more and more of its own weight will be too large. Ever since the conception and development of the carbon nanotube, the space elevator has been a realistic possibility. Carbon nanotubes have the greatest specific strength of any material currently in existence and can enable a taper ratio of 1.5 in theory [1]. For comparison, steel will have a taper ratio of 10^{52}, which is well over the width of the universe [4]. Furthermore, the material that makes up the tether must be resistant to the variety of environments that sections of the cable will experience. The space elevator must be able to withstand numerous abuses, including severe weather within the atmosphere, radiation in the Van Allen Belts, and debris in space. Carbon nanotubes meet the physical requirements necessary to endure these conditions. In addition, an epoxy is used to bind the relatively short segments of nanotubes together at regular intervals. The epoxy is durable and strong and forms a composite with carbon nanotubes. Other materials similar to carbon nanotubes, such as boron nitride nanotubes and diamond nanothreads, have also been made with extremely high specific strengths [5]. However, their strength and ability to be manufactured has not been researched enough to be considered for the construction of a space elevator in the present or near future.

4.2 Microscopic Structure

Carbon nanotubes are a solid allotrope of carbon constructed from sheets of graphene. These sheets are configured in a cylindrical structure with diameters of approximately 10 angstroms [6]. In the context of a space elevator, single-walled nanotubes, or SWNTs, which can be viewed as one roll of graphene, are preferred because they have been studied more extensively in terms of tensile strength than multi-walled nanotubes (MWNTs) and will therefore offer more reliable data on which to base calculations. In addition to the number of graphene layers, the pattern in which the graphene is bonded together also has a significant impact on the mechanical and electrical properties of the nanotube. The three types of configurations for SWNTs are armchair, zigzag, and chiral, which are based on the vector axis from which a graphene sheet is rolled. In terms of the feasibility of a space elevator today, zigzag SWNTs are the best option because they deform the least [7]. Deformation is bad for the construction of a space elevator because the tensile strength of the cable cannot be predicted accurately after deformation occurs and could cause unknown consequences. Despite the fact that zigzag SWNTs deform the least, they also are the most brittle and break under the least strength. This “least strength,” however, is still strong enough for the cable of a space elevator, even with a safety factor of 1.25.

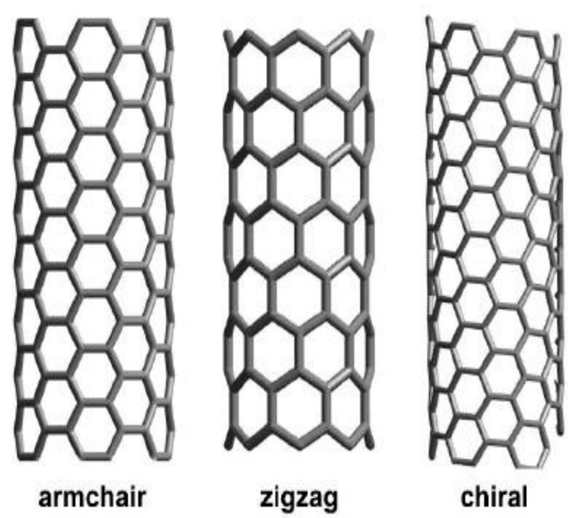

Figure 2: Carbon nanotube microstructure designs [6]

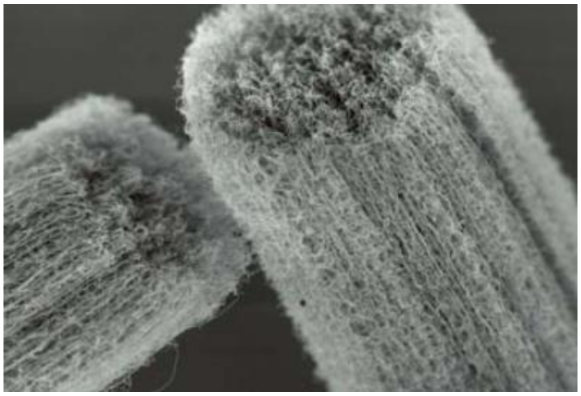

Figure 3: Scanning electron microscopy image of carbon nanotube bundles [8]

4.3 Macroscopic Structure

4.3.1 3D Renderings

The macroscopic structure of the tether is critical to the success of the space elevator. Specific weaves or patterns can allow a greater tensile strength than simply gluing carbon nanotubes together in parallel. Also, a resourceful and clever design can give the cable resistance to weather, space debris, and other dangerous exposure. In SolidWorks, several cable designs were tested with a custom configured nanotube material and subjected to tensile forces to measure the stress on points in the design.

The first design that was modeled in SolidWorks was proposed in 2000 by Bradley C. Edwards [1]. For the purposes of this study, it shall be referred to as the Standard Model. It consists of layers of carbon nanotubes aligned vertically to form a curved ribbon. This curved shape is preferred as it would reduce potential damage from debris impacts. These tubes are connected by horizontal braces made of a carbon nanotube and epoxy composite. The entire ribbon is reinforced by two vertical carbon nonotube (CNT) ribs. The design rendered in SolidWorks is enlarged, with tubes 1 mm in diameter. The design is 40 mm wide, 1.5 mm thick, and 104 mm in height.

The second design, called the Hoytether, was proposed by Robert Hoyt as an alternative to the Standard Model [1]. It consists of a lattice of vertical CNTs and diagonal CNTs forming a diamond pattern. The Hoytether design provides a possible solution to the issue of space debris impacting the tether. If a vertical member is severed, the diagonal members are designed to stretch and assume the load of the severed CNT. In this way, the tether will be able to adapt to and weather minor damage incurred by space debris. The render in SolidWorks represents a small cross-section of a Hoytether ribbon. It is enlarged, measuring 15 mm in width and 20 mm in height. The CNTs are 1 mm in diameter.

The third design is a Hybrid between the Standard Model and the Hoytether. It retains the ribs, curvature, and carbon nanotube/epoxy composite of the first design, but replaces the vertical nanotubes with the Hoytether weave. However, the Hoytether diamonds are widened to make this Hybrid considerably lighter than the traditional Hoytether design. While the Hoytether allows for resistance to debris, the tensile strength of the Standard Model is maintained in this Hybrid through the thick vertical ribs. This model was increased in scale considerably, with each nanotube having a radius of 0.5 mm. The entire height of this section was 20 mm, and its width was 46.7 mm from end to end.

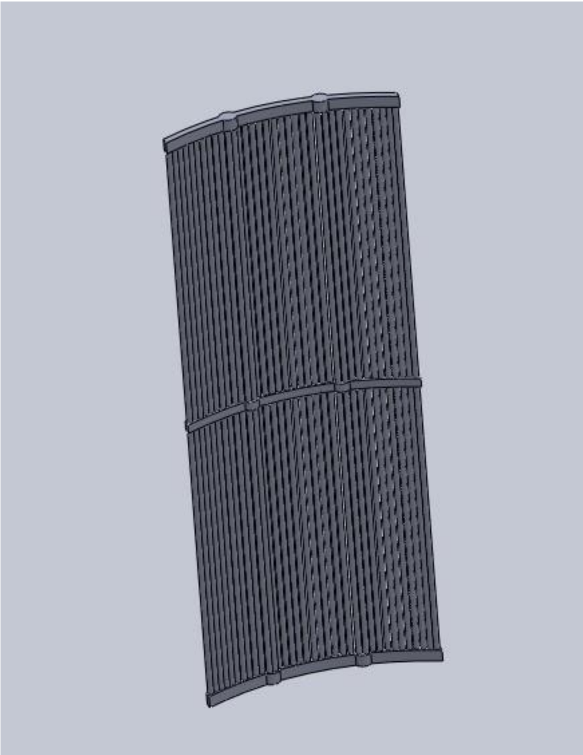

Figure 4: Standard Model

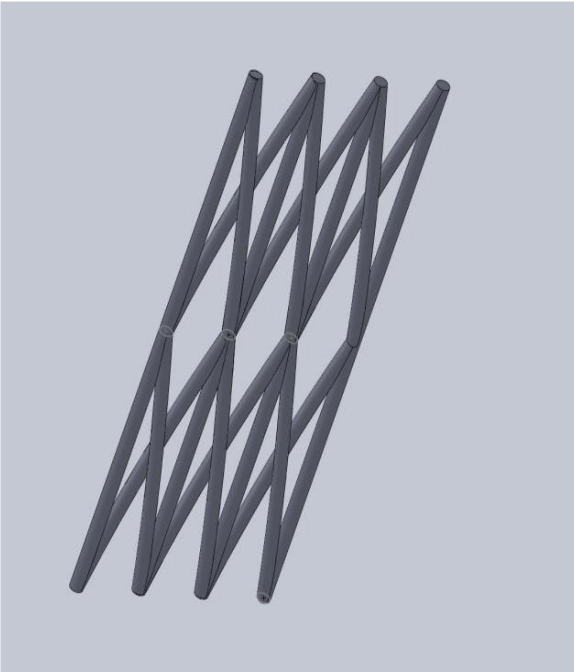

Figure 5: Hoytether Model

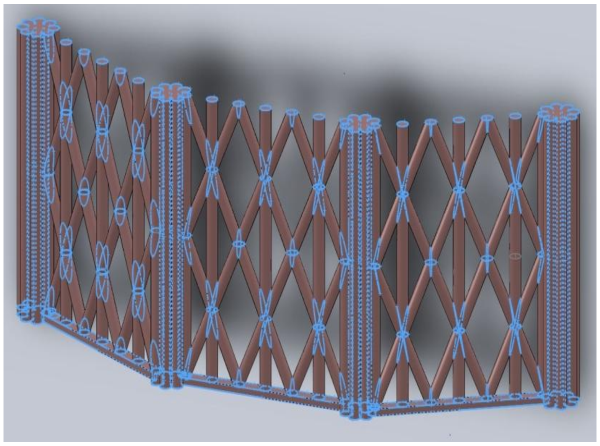

Figure 6: Hybrid Model

4.3.2 Calculations Regarding the Cable

In order to adequately analyze the feasibility of a space elevator, it is necessary to understand the dimensions and structure of the entire elevator beyond just the cable. As mentioned earlier, the elevator will consist of a tapered tether with a counterweight on the end. The tether will widen as it reaches GEO in order to support the weight below it. In addition, the counterweight serves to maintain the elevator's center of mass slightly above GEO, obviating the need for another 108,000 km of tether. The equations and values below describe the macroscopic specifications of the contemporary space elevator, such as tensile strength, taper ratio, length of the cable, and the mass of the counterweight.

Tensile strengths for nanotubes from numerous independent scientific studies have been averaged to calculate a realistic tensile strength of a cable that could be fabricated today. These values - 11, 11.7, 22.1, 36.01, 52, 57.33, 59.8, 63, 94.51, and 200 GPa - result in an average of 60.75 GPa, which represents the stress at which a CNT tether would most likely break. However, the tether must not be under this level of stress. Instead, the tether should experience stresses approximately 0.8 times the breaking stress. This gives the elevator a comfortable factor of safety of 1.25. Thus, for the purposes of these calculations, the mean stress acting on the elevator will be 48.60 GPa. However, since a sample mean was produced, a confidence interval was necessary in order to describe its accuracy. To 80% confidence, it is known that the population mean of the carbon nanotubes that have been experimentally tested and could be constructed today is between 29.37 and 67.82, assuming a safety factor of 1.25. Using this range, it is possible to calculate the probable bounds of taper ratio of a space elevator, which end up being 2.53 and 8.55 using Equation 1 below. All ratios within this bound are reasonable in terms of feasibility today.

$$\frac{A_g}{A_s} = exp\left[\frac{R\rho g}{2T}\left\{\left(\frac{R}{R_g}\right)^3 - 3\left(\frac{R}{R_g}\right) + 2\right\}\right]$$

Equation 1: Taper Ratio

A_g is the cross-sectional area of the cable at geostationary orbit in m^2. A_s is the cross-sectional area of the cable at sea level in m^2, which is set to 10.5 μm^2. R is the distance from the center of the Earth to sea level in m. R_g is the distance from the center of the Earth to geostationary orbit in m. T is the tensile stress of the cable in Pa. ρ is the density of the cable in $\frac{kg}{m^3}$ and g is the gravitational acceleration on Earth, 9.807 $\frac{m}{s^2}$. The taper ratio of the cable with a tensile stress of 48.60 GPa was found to be 3.66.

For any further calculations, only the average tensile stress and the resulting average taper ratio will be used for the sake of clarity and specificity.

The mass of the counterweight is given by the following equation.

$$m_c = \frac{\rho A_s T exp\left[\frac{R^2\rho g}{2TR_g^3}\left\{\frac{2R_g^3+R^3}{R} - \frac{2R_g^3+(R_g+h)^3}{R_g+h}\right\}\right]}{\frac{R^2(R_g+h)}{R_g^3}\left[1-\left(\frac{R_g}{R_g+h}\right)^3\right]\rho g}$$

Equation 2: Counterweight Mass

m_c is the mass of the counterweight in kg and h is the height of the counterweight above geostationary orbit at 35,786 km, in m. However, since the mass of the counterweight is dependent on this height, h, counterweight masses for distances ranging from 30,000 km to 100,000 km beyond GEO were compiled. Parts of the analysis are shown in the chart below and it was decided that a total length of 116,000 km and mass of 1375 metric tons would be the best balance between height and mass in terms of the ability of aeronautics agencies to launch the elevator into space.

Table 1: Counterweight Mass vs. Height Above Geostationary Orbit

Height beyond GEO (km)	**Mass of Counterweight (metric tons)**
30,000	5270
40,000	3910
50,000	2900
60,000	2300
70,000	1780
80,000	1380
90,000	1060
100,000	812

Finally, after determining the mass of the counterweight and the taper ratio, as well as setting the sea level cross-sectional area to 10.5 μm^2, the following equation was used to calculate the mass of the cable itself.

$$m_e = \rho \int_{R}^{R_g+h} A(r)\, dr$$

Equation 3: Cable Mass

m_e is the mass of the cable and A(r) is a function of the cross-sectional area of the cable based on height from the center of the Earth. It was found that the mass of the carbon nanotube cable would be 3438 metric tons.

4.4 Stress Analysis

SolidWorks lacks the capability to test a full scale cable. For this study, smaller, enlarged segments were tested under tension to analyze the resulting stress on different parts of the segments. Using SolidWorks' SimulationXpress program, a load proportional to each model's volume was placed on the end of each design, and the opposite ends were fixed, putting each design under tension. A custom material was created for the simulations to emulate the properties of carbon nanotubes.

Table 2: Custom Material Properties

Property	Value
Elastic Modulus	950 GPa [9]
Poisson's Ratio	0.1 [10]
Shear Modulus	1 GPa [11]
Tensile Strength	63 GPa [9]
Yield Strength	63 GPa
Mass Density	1300 kg/m^3 [12]

For the Standard Model a force of 95,440 N was exerted. 8,000 N was exerted on the Hoytether and 230,200 N was exerted on the Hybrid. Then, holes were extruded through each design to simulate meteor damage, and the designs were re-tested under the same loads. Only the Standard Model and the Hoytether, however, could be successfully tested with the meteor damage. The damaged Hybrid design overwhelmed SolidWorks' limited analytical faculties and could not be tested. The tests on the Standard Model revealed numerous advantages and deficiencies in the design.

Table 3: Stress Analysis

Design	Load (N)	Least Stress (GPa)	Greatest Stress (GPa)	Factor of Safety
Standard Model	95440	0.0025	.4169	151.08
Standard Model with Holes	95440	$6.3 * 10^{-9}$	2.104	29.94
Hoytether	8000	0.0473	58.461	1.077
Hoytether with Holes	8000	$3.47 * 10^{-7}$	59.444	1.059
Hybrid	230,200	0.0324	9.7756	6.446

4.4.1 Standard Model

The Standard Model is the strongest of the three base designs. The greatest stress experienced by the undamaged design was 0.417 GPa, which is miniscule when compared to the 58.5 GPa and 9.78 GPa experienced by the Hoytether and Hybrid, respectively. From the stress distribution diagram of the model, it is apparent that the two vertical ribs are bearing the brunt of the stress, having slightly higher stresses than the surrounding vertical strands. In addition, it was found that the horizontal ribs experience significantly less stress than the bare nanotubes as a result of more surface area, since there is empty space between the circular nanotubes. Though the ribs are a composite blend of nanotubes and epoxy with a lower specific strength than the bare nanotubes, the lower stress in this area means the cable would be stable with the regularly spaced linking system (see Figure 7 in Appendix).

When segments are removed from the model to simulate meteor damage, the Standard Model still proves itself to be the strongest, experiencing a maximum stress of 2.104 GPa. However, this is still a significant decrease in strength from the undamaged model. The undamaged Standard Model's factor of safety (FOS) is 151.09, but it drops to 29.95, a fifth of its former FOS when the model is "damaged." This illustrates that, as strong as though it may be, the Standard Model is ill-equipped to adapt to meteor damage. Any kind of damage simply compromises the integrity of the tether by too large a factor (see Figure 8 in Appendix).

4.4.2 Hoytether

The Hoytether design was the weakest of all the designs, experiencing stresses up to 58.461 GPa, almost as much as the breaking point of the CNTs. This would be undesirable in a tether design when there are better alternatives available. It is important to note that most of the stress was concentrated at the joints of the model (see Figure 9 in Appendix).

Perhaps the most significant result from this test was the performance of the damaged Hoytether weave. Under the same stresses as the undamaged model and with numerous holes in the vertical members, the damaged model experienced a maximum stress of only 59.444 GPa, a mere 1.6% greater than the stress experienced by the undamaged model. The FOS between the undamaged and damaged models decreased marginally, from 1.077 to 1.0598. As Hoyt predicted, it is clear in the stress diagram that the diagonal members successfully bore the load after the severance of the vertical strands. Despite its structural weakness in comparison to other designs, it is clear that the Hoytether is the most resilient of the designs in the face of debris damage (see Figure 10 in Appendix).

4.4.3 Hybrid Model

The Hybrid Model, though not as strong as the Standard Model, was stronger than the Hoytether, as evidenced by Table 3. Unfortunately, no more data is available, as the "meteoroid damaged" design could not be tested. However, because it utilizes the Hoytether's weave between its vertical ribs, it should retain much of the Hoytether's resilience in dealing with meteoroid damage. It also employs the strong vertical ribs and composite cross-sections of the Standard Model, making its strength superior to the Hoytether's (see Figure 11 in Appendix).

4.4.4 Conclusions and Error

Before drawing any conclusions from the data, it is imperative that readers recognize that SolidWorks was not designed to model nanostructures or to perform complex stress analyses on those structures. As such, the models and tests performed in SolidWorks have large margins of error. It is likely that, in the 3D rendering process, not all variables were controlled for between each of the three base designs. While the comparison between damaged and undamaged renderings of a given model is reliable, it is unlikely the three base designs can be compared with complete accuracy. Nonetheless, there are numerous important general conclusions that can be drawn from this experiment. It is reasonable to assume that, though vastly exaggerated through the SolidWorks rendering, the Standard Model is the strongest, followed by the Hybrid and then the Hoytether. Additionally, it is highly likely that the Hoytether is indeed more resilient and adaptable than the Standard Model when damaged by space debris. Thus, it can fairly be concluded that the Hybrid Model should improve upon the strength of the Hoytether, while still improving upon the resilience of the Standard Model. Therefore, it would be most advantageous to weave the tether in the Hybrid configuration.

5. Deployment

5.1 Launch and Unspooling

Previous studies have based launching the system off of older technology, but rocket science has greatly advanced in recent years. This study finds the capabilities of the upcoming Falcon Heavy rocket, manufactured by SpaceX, to be suitable. The vehicle can carry 22,200 kg to Geostationary Transfer Orbit (GTO) for $90 million [13]. By comparison, the Space Shuttle can carry 3,810 kg to GTO, and estimates of launch prices range from $450 million to $1.5 billion [14]. Thus, the Falcon Heavy costs around 2% of the Shuttle's costs, per kilogram. With four launches, a very capable ship can be constructed in GTO. The spacecraft will need chemical thrusters and propellant in order to remain vertical while releasing the cable (see section 2.3). Complex spooling mechanisms can be constructed to carefully, yet rapidly release the cable downwards. The craft will extend the cable while simultaneously moving away from the Earth. Eventually, the lower end will reach the surface and the upper end, along with the craft itself, will reach the full extended length to serve as a counterweight.

The initial area of the cable at the base will be a mere 0.105 mm^2. The mass of the counterweight will need to be 13,751 kg and the actual mass of the spacecraft after deployment will total 14,000 kg to keep the center of mass far enough above GEO. The mass of the cable itself will total 34,380 kg. In addition, 40,000 kg of propellant will be allocated to the spacecraft for orbital correction and insertion. The entire mass can be carried in 4 Falcon Heavy Launches for a cost of $360 million.

5.2 Reinforcement

The initial ribbon will be very thin to save mass and size in the spacecraft and thus, can support only smaller climbers at first. The first climbers -- roughly 200 -- will serve to immediately reinforce the cable by attaching new ribbons as they move upwards. The final cable mass and area will be 100 times the initial quantities. This gradual process will not only enable much larger payloads to climb, but will also serve as protection against weaknesses in the cable.

6. Climbers

6.1 Design

The climbers will use a simple mechanical system to climb the cable through the use of traction. Though others have proposed electromagnetic propulsion [15], this is nearly impossible for a first elevator, and also unnecessary. The infrastructure required is complicated and massive. It is, however, an excellent alternative for future elevators built using the first, and can support humans because of its capability to accelerate quickly. The underside of the climber will carry solar panels. Depending on the necessity, the climber can be sealed and pressurized, although preliminary climbers will not be, in order to save mass. The rest of the climber will carry the payload.

6.2 Power

Many studies suggest using the conductive properties of carbon nanotubes to send electricity through the cable itself [15]. However, this system poses serious risks; namely, a vast amount of energy will be lost on the very long cable, and the heat generated by this can damage the epoxy and weaken the cable. Instead, a laser beaming system is recommended. The climbers will have solar panels mounted on their undersides. A facility located on the surface of Earth will further focus the lasers using optics to concentrate the beam. The climbers will then convert this energy to mechanical power. Atmospheric distortion must also be accounted for. Some studies suggest larger solar panels to maintain efficiency [1]. However, this adds more mass to the climbers, which matters greatly in the early phases. If the lasers instead increase their output as the climber ascends, the difference will be accounted for by the greater intensity of light from the laser. Energy will be lost, but the expenditure will be reasonable. Recent advances in lithium-ion battery technology allow for excellent power storage systems. This allows for operation even during laser failures or shortages and also enables regenerative braking, thus saving total energy expenditure.

7. Location

7.1 Sea-going Platform

A sea-going platform will be constructed or refurbished for use as the space elevator's anchor point. For example, a floating oil rig can be repurposed. A sea-going platform will be the most feasible for several reasons. By international law, international waters cannot be claimed by a country [16]. Thus, establishing a sea-based platform will remove much potential political drama. In addition, mobility is a necessity for the elevator. Orbital objects and weather systems can be avoided if the cable can move.

7.2 Geographical Location

A location around 2,500 kilometers west of Ecuador, on the equator, was selected as the best location for various reasons. First, its location on the equator will let the elevator move faster at lower heights, reducing the necessary length. In addition, this location is far less prone to extreme weather. Tropical storms can neither form on, nor cross the equator due to the Coriolis Effect. In addition, the equator in general, and particularly this location, sees virtually no lightning and little rain or wind, reducing weather complications [1].

8. Solutions to Other Complications

8.1 Avoiding Meteoroids, Space Debris, and Satellites

Even debris as small as a golf ball can demolish the entire space elevator. However, objects in orbit can be tracked and avoided. In addition, existing satellites must be avoided by law, and will need to be given a wide area to pass through unharmed [17]. This can be accomplished by moving the anchor-barge roughly a kilometer in any direction to send a pulse up the cable. Many studies simply recommend moving when necessary to avoid an object [1]. However, these pulses can build up along the length of the elevator, and cause chaotic motion at certain points. Therefore, a second pulse back to the original position is recommended when any given pulse returns to ground level. This will cancel out the vibrations and allow for stable climbing on the tether.

8.2 Atomic Oxygen

Atomic oxygen is a pertinent problem when considering the construction of a space elevator. Atomic oxygen, which is essentially single oxygen atoms that exist high in Earth's atmosphere, is extremely reactive due to the valence electrons on a free oxygen atom. Thus, any material exposed to atomic oxygen for substantial periods of time will inevitably undergo corrosion. In fact, organic elements such as carbon are especially susceptible to the oxygen. To remove the debilitating impacts that atomic oxygen can have on a space elevator, the most feasible solution is to coat the surface area of the carbon nanotube composite with another element that will resist bonding with oxygen atoms. In tests conducted by NASA and Russia using the Hubble Space Telescope and the Mir Space Station, it was found that aluminum, gold and platinum are the least reactive to atomic oxygen [18]. By conducting further tests, it was concluded that aluminum is the best option as it is a lightweight, non-reactive material that could coat the space elevator without severely harming its function or weight. The only impact this coating would have on the space elevator is decreasing its strength to weight ratio a small amount, which would be accounted for in the taper ratio. It will not cause significant changes in any other aspects of construction.

8.3 Radiation

Radiation must be accounted for in the design of the elevator and cable. It is nearly impossible for the path of the cable to avoid exposure to some sort of radiation, whether in the form of sun particles, galactic cosmic rays, or the intense exposure that will be experienced due to the Van Allen Belts [19]. The Van Allen Belts are regions of radiation that wrap around the earth and fluctuate in intensity, particularly around the equator. If a human was to travel up the cable without proper shielding on a space elevator, the high dosage of radiation received will be enough to cause serious medical problems, including death [19]. The technology, not only humans, will be affected by such high dosage rates. Any sensitive equipment brought aboard the machines may malfunction or experience irreparable damage leading to catastrophic failures. Hence, it is imperative that the elevator and any climbers sent along the cable are under consistent protection from radiation. Aluminum is the standard for radiation shielding due to its light weight and the effective protection it offers. However, any advances in this area that would optimize the mass to shielding ratio should be taken into consideration.

8.4 Weather

As stated above, most potentially harmful weather will be naturally avoided due to the anchor's strategic location on the equator, west of Ecuador. Other dangerous systems can be avoided by temporarily moving the platform elsewhere. Only calm rain and winds will reach the elevator, and the safety factor of the cable means that these events will not be harmful to the structure.

8.5 Political Considerations

Placing the anchor in international waters enables political freedom. In addition, the Outer Space Treaty declared that "outer space...is not subject to national appropriation [20]." Therefore, the political stability of the elevator is ensured by multiple international treaties. By the Space Liability Convention, the operator of the elevator will be held liable to damage caused by it [17]. Maneuvers will need to be timed to properly avoid any collisions with satellites crossing the equatorial plane.

8.6 Effects of a Catastrophic Failure

In the event of a catastrophic failure, wherein the cable is severed at one or more points, the fallout will not be severe. No matter where the cut occurs, the upper portion of the cable will be flung outwards into space to a relatively safe location. Although the exact result depends upon the height of severance, in general, higher segments of the remaining ribbon will burn up in the atmosphere relatively harmlessly. Lower portions will largely land in the ocean, and will be travelling at a low enough velocity that very little impact damage will occur. Thus, the effects of a catastrophic failure will not pose serious health risks [21].

9. Conclusions and The Future

9.1 Conclusion

This study finds that the space elevator cable must be made from single-walled carbon nanotubes, as they are the only suitable material for making a space elevator that is available today. In addition, the cable should use the Hybrid Model, the mix of the Hoytether and Standard Models, for its design. The anchor on Earth should be located west of Ecuador to avoid weather issues and take advantage of the high radial velocity at the Earth's equator. After the initial cable is deployed, additional climbers will traverse the cable to strengthen and repair the cable from damage, such as atomic oxygen and meteors. The climbers will be powered by a laser beamed from the base to a solar panel on the climber. When completed, the space elevator will provide a cheap, efficient alternative method for space exploration as opposed to the traditional method of launching rockets. Provided that carbon nanotubes can be mass produced in the quantities and specifications required, and that the economic, legal, and political barriers can be overcome, this study concludes that modern technology is indeed sufficient for the construction of a space elevator.

9.2 Future Developments

The space elevator described in this paper will only be a first step. The first space elevator will certainly be used to build more complex and larger elevators. Future developments in electromagnetic propulsion will allow for human transport through the Van Allen radiation belts at a high speed, reducing exposure and allowing for human settlements in Earth orbit. Thus, the first veritable space city can be constructed with a reasonably large population. It is likely that many elevators, under different owners, will eventually reach into space. Space elevators will not be confined to Earth, but rather will likely be built on the Moon and Mars, allowing for the exploration and development of those now-remote locations. Asteroid mining will become a truly feasible and profitable prospect. Space elevators will be a stepping stone for humanity's future exploration and colonization of space, the catalyst necessary to broach humanity's final frontier.

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Appendix

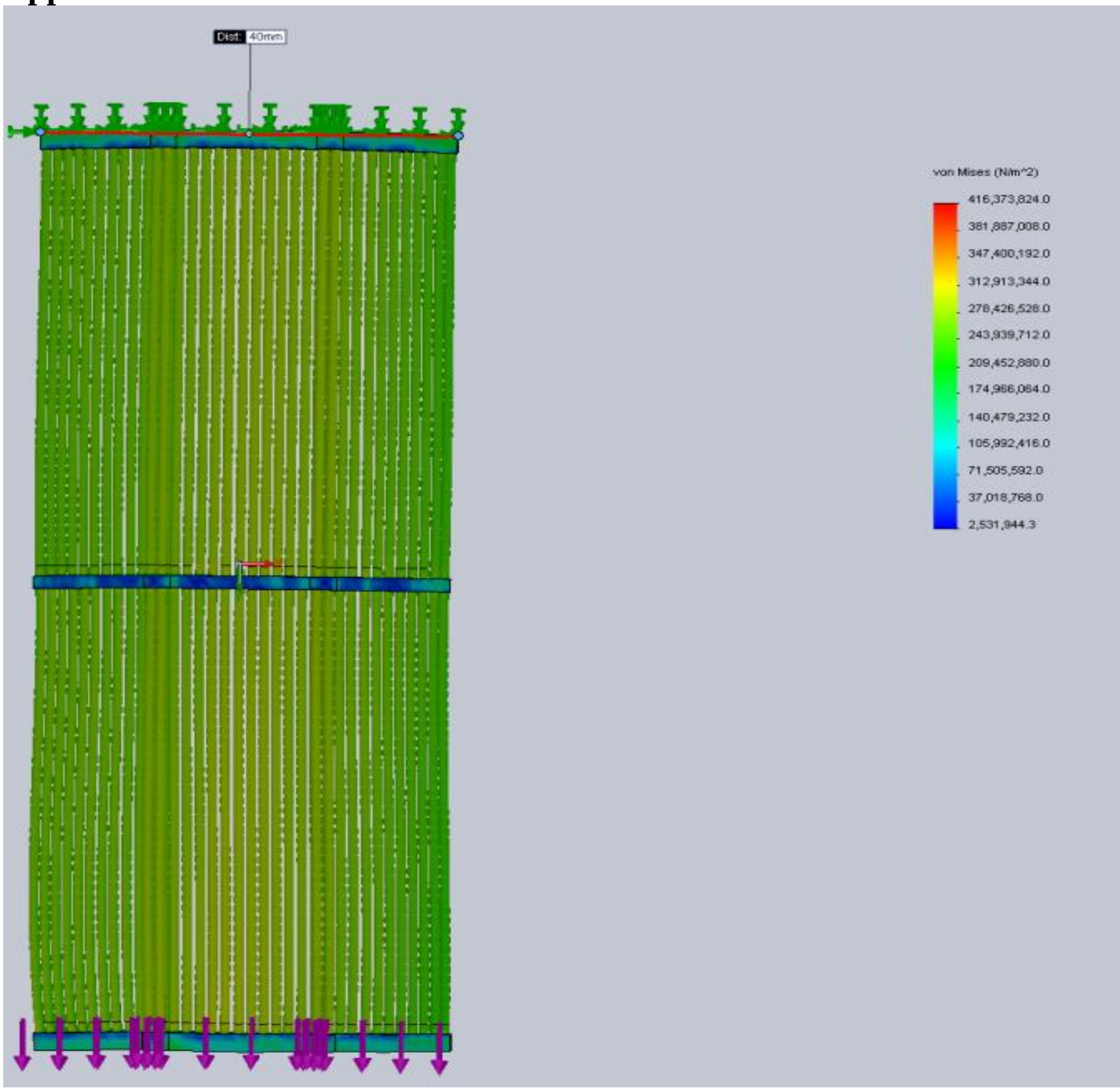

Figure 7: The Standard Model is under stress with the blue epoxy composite ribs experiencing less stress. The purple arrows are loads attached to the model, while green arrows are fixed points on the model. As per the metric on the right of the image, blue regions experience less stress than green region.

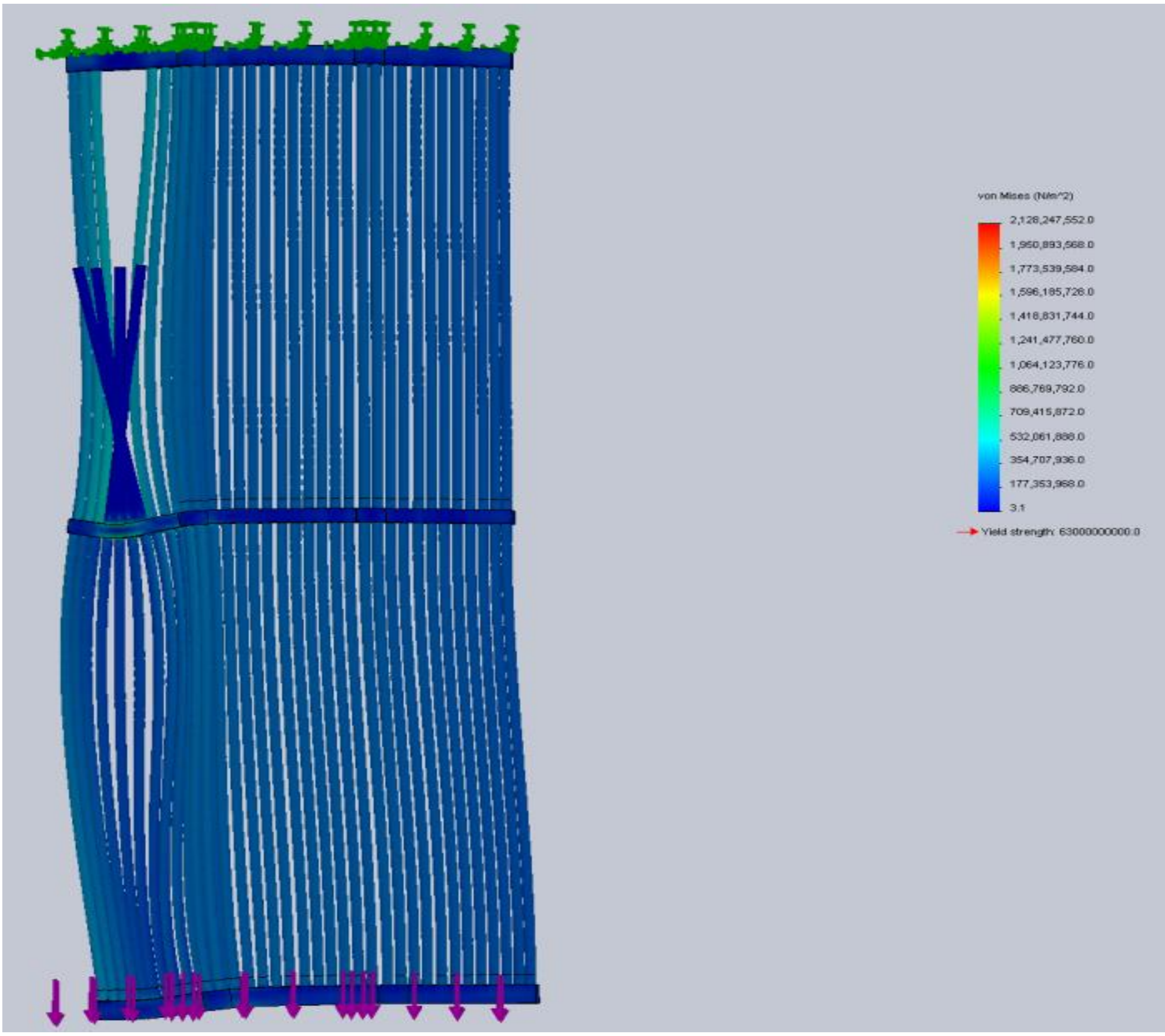

Figure 8: The damaged Standard Model design has a large hole in it to mimic performance after meteor damage. While it looks blue, the colors on the metric correspond to different values as those in Figure 7.

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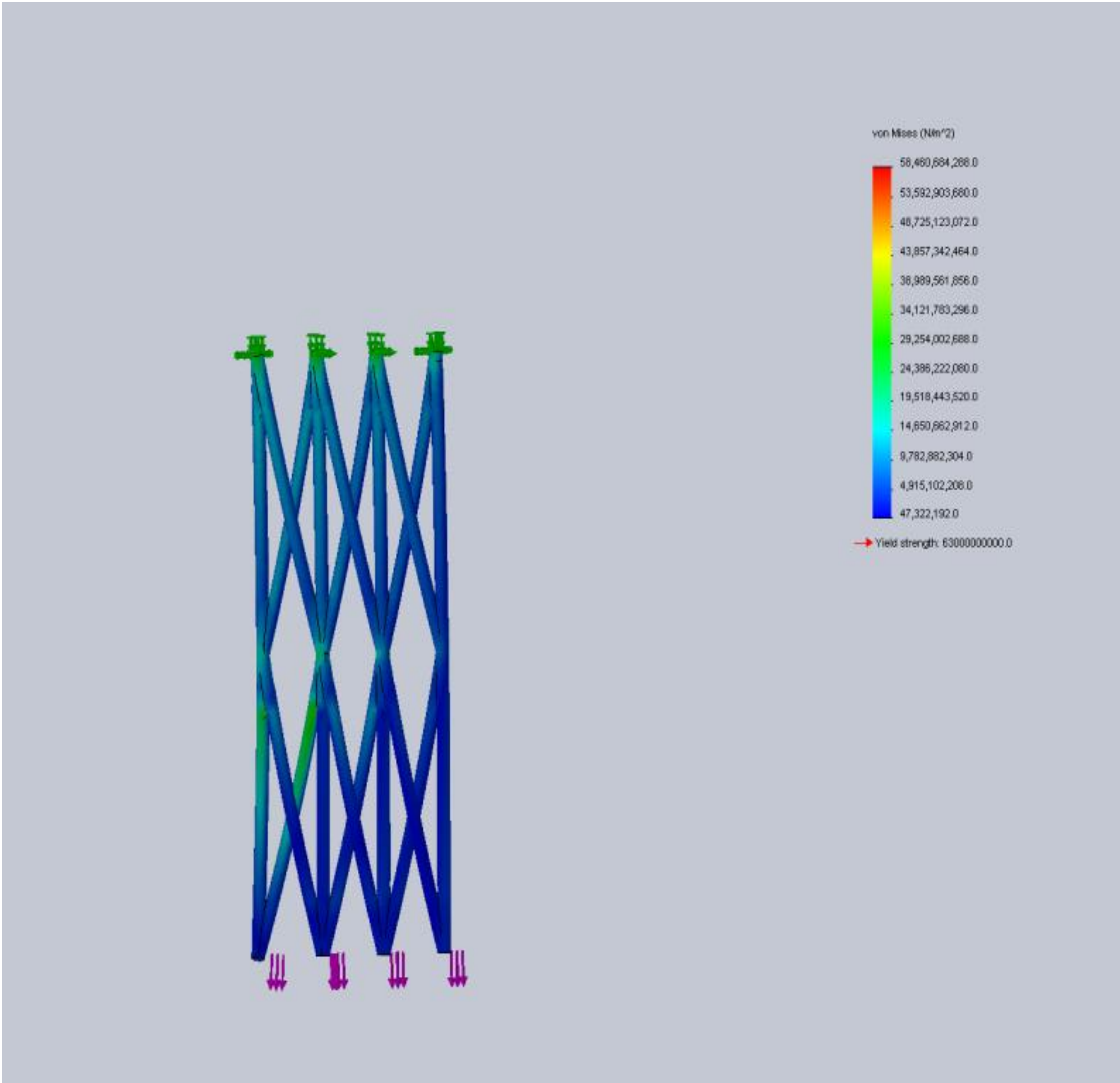

Figure 9: The Hoytether Model under stress.

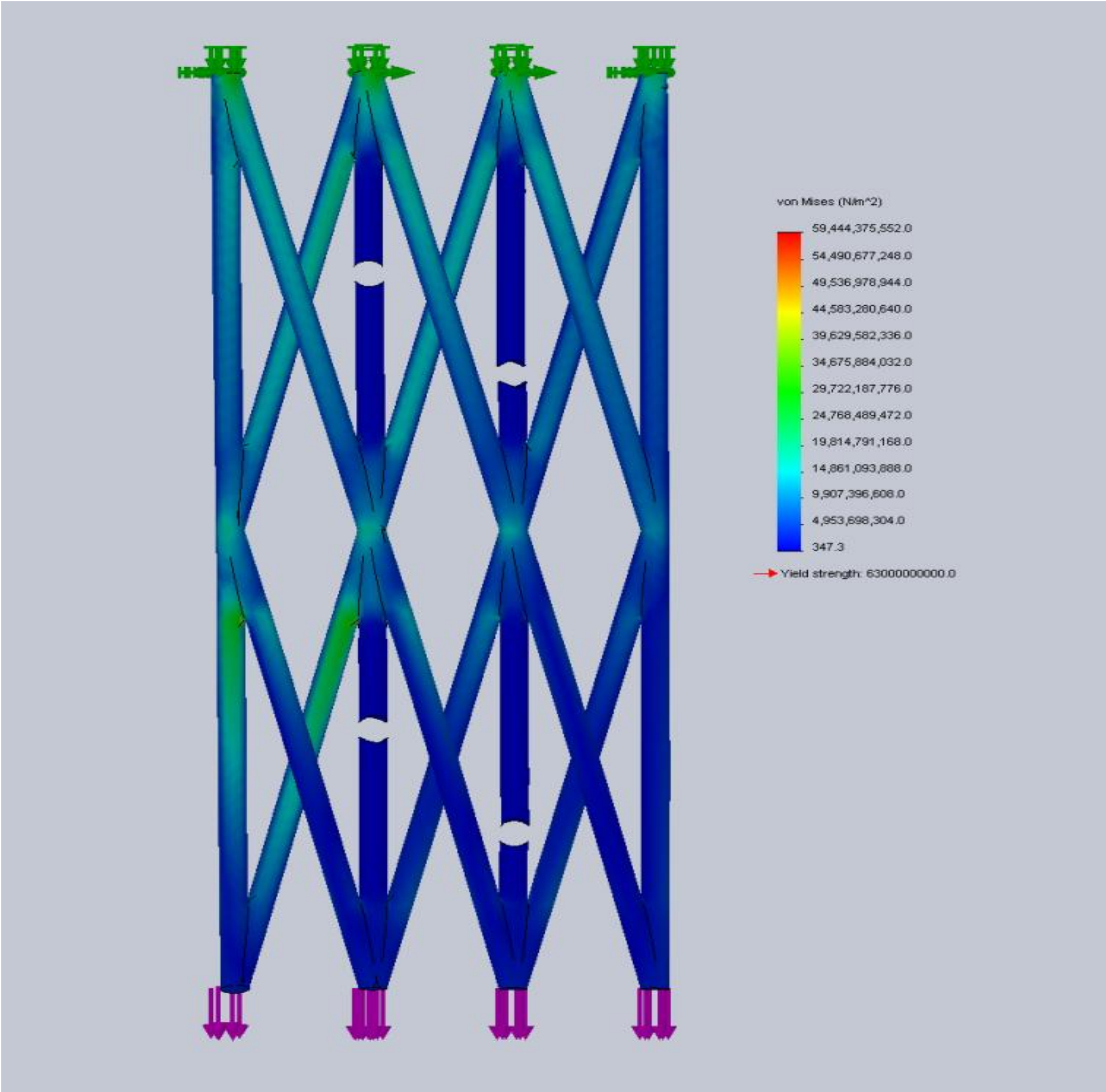

Figure 10: The "damaged" Hoytether Model, with holes to mimic performance after meteor damage.

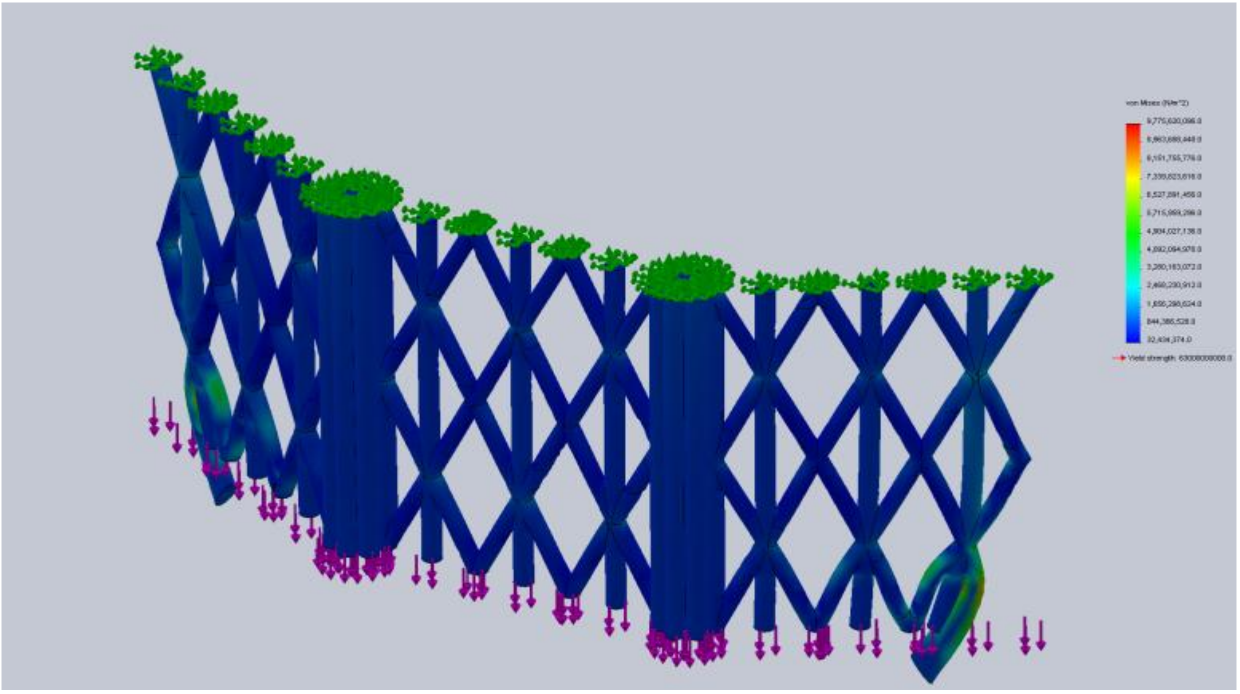

Figure 11: The Hybrid Model under stress.