Modular Carbon-Nanotube Tether Architecture for Space-Elevator Deployment: Design, Modelling, and Feasibility Assessment

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Abstract

The major obstacle to an Earth-to-geostationary space elevator is the fabrication and long-term survival of a 100 000 km tether whose *specific* tensile strength exceeds $45\,\mathrm{GPa\,cm^3\,g^{-1}}$. While laboratory carbon-nanotube (CNT) yarns now meet this metric, scaling a *monolithic* ribbon remains out of reach. We propose a *modular* tether composed of repeatable 10 km to 100 km segments joined on-orbit by nanobonded sleeve couplers. Static and dynamic models show that, with an optimised taper and joint preload, the segmented system approaches the load envelope of an ideal ribbon while enabling in-situ replacement of damaged spans. Finite-element and lumped-parameter simulations quantify failure modes—joint delamination, micrometeoroid puncture, thermo-elastic cycling—and demonstrate margin against worst-case GEO wind loading. Deployment logistics indicate a 35 % launch-mass reduction relative to monolithic concepts, and a mean time to repair under 72h for a representative 50 km segment. These results re-frame the space-elevator challenge as a systems-engineering problem amenable to near-term industrial capability. (Will make sure to rewrite this)

Keywords—space elevator, carbon nanotubes, modular tethers, orbital infrastructure, megastructures

1 Introduction

Since Konstantin Tsiolkovsky first sketched a *"celestial castle"* in 1895, the space-elevator concept has promised an Earth-to-orbit logistics revolution, replacing expendable chemical rockets with electrically powered climbers ascending a stationary tether anchored near the equator and extending beyond geostationary orbit (GEO). Analyses by the NASA Institute for Advanced Concepts (NIAC) suggest cost reductions of one to two orders of magnitude per kilogram to orbit [1, 2].

The tether must sustain axial tensions approaching 60 GPa over 100 Mm while minimising self-weight. High-performance polymers such as Kevlar, Zylon and T1000 carbon fibre fall short, with specific strengths of only $25\,\mathrm{GPa\,cm^3\,g^{-1}}$ to $30\,\mathrm{GPa\,cm^3\,g^{-1}}$ [3, 4]. Carbon-nanotube (CNT) assemblies outperform these materials; laboratory yarns now exceed $50\,\mathrm{GPa\,cm^3\,g^{-1}}$ [5, 6], and pilot lines have demonstrated kilometre-scale continuous production at throughputs above 100 km/day [7]. Yet a defect-free 100 000 km monolithic ribbon remains infeasible and essentially unserviceable once deployed [8, 9].

Modular or *segmented* architectures therefore merit renewed attention. Shorter segments simplify quality control, permit phased mass-optimised tapering, and allow on-orbit replacement of damaged lengths. Despite several conceptual studies [10], a rigorous treatment of load-path continuity, joint reliability and system-level dynamics is still lacking.

Objectives—This study:

1) Specifies a modular CNT tether architecture (segment length, graded cross-section, sleeve-coupler design);

2) Derives closed-form tension and vibration envelopes for the segmented tether under Earth gravity and centrifugal fields;

3) Uses finite-element and lumped-parameter models to quantify joint delamination, micrometeoroid damage and thermo-radiative cycling;

4) Evaluates deployment and repair logistics, including launch-mass savings and sequence optimisation.

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Paper Structure—After the Abstract (§**??**) and Introduction (§1), the manuscript proceeds as follows:

1) **Related Work / Literature Review** (§2)—historical and current space-elevator studies, tether-material advances, and modular-structure research gaps.
2) **Theoretical Foundations** (§**??**)—orbital-mechanics constraints, tapering equations, CNT mechanical properties, and environmental loads.
3) **System Design Proposal** (§3)—(5.1) modular segment architecture, (5.2) CNT material hierarchy, and (5.3) deployment logistics.
4) **Simulation & Analysis** (§**??**)—static/dynamic stress models, failure-mode spectra, and thermal–radiation environment modelling.
5) **Results** (§**??**)—stress profiles, modularity–strength trade-offs, mass efficiency, and thermal-resilience metrics.
6) **Discussion** (§**??**)—implications for manufacturability, repairability, and scalability to a 100 000 km tether.
7) **Future Work** (§**??**)—laboratory prototypes, vacuum-joint testing, micro-gravity demonstrations, and hybrid-material exploration.
8) **Conclusion** (§**??**)—summary of findings and the modular CNT tether's significance for space-elevator feasibility.
9) **References** (§3.1) and, as needed, **Appendices** (§**??**) containing full derivations, simulation parameters, and supplementary figures.

2 Related Work / Literature Review

The literature on space-elevator tethers can be grouped into six mutually reinforcing themes: architectural segmentation, nanoscale material advances, tether dynamics, deployment logistics, risk-mitigation strategies, and economic viability.

2.1 Tether Architecture and Modularity

Early feasibility studies assumed a monolithic, exponentially tapered ribbon [1], but recent work shows that subdividing the tether into *repairable modules* can relax peak-stress requirements and simplify maintenance. Luo *etal.* quantified the stress redistribution achievable with 10 km to 100 km segments joined by sleeve couplers, reporting a 22 % reduction in maximum axial stress relative to an equivalent continuous tether [11]. Popescu and Sun introduced a bio-inspired bundle architecture in which individual sub-cables can break and be robotically replaced, analogous to tendon remodelling, thereby trading higher operating stress for active self-repair [12]. The International Academy of Astronautics (IAA) Study Group 3.10 recommended a one-metre-wide woven ribbon whose many parallel CNT yarns provide in-plane redundancy [13]. These studies converge on the conclusion that *segmented or multi-strand* topologies offer a feasible path to incremental construction and lifetime resilience.

2.2 Carbon Nanotubes and Competing High-Strength Nanomaterials

Carbon nanotubes remain the reference material for an Earth elevator thanks to laboratory strengths in the 40 GPa to 80 GPa range and specific strength >30 M [5, 6]. Industrial spinning lines now produce kilometre-scale CNT yarns (¿100 km day^{-1}), but their tensile strength is still dominated by inter-tube slippage and defect statistics [14]. Alternative candidates include single-crystal graphene ribbons, boron-nitride nanotubes (BNNTs), and diamond nanothreads, each offering unique radiation or thermal advantages but facing steeper manufacturing barriers [15]. Most authors agree that closing the gap between laboratory samples and 100000-km production will require continued progress in defect suppression, spin alignment, and surface passivation against atomic-oxygen erosion.

2.3 Tether Dynamics and Control

The tether is a tapered, tensioned string with coupled longitudinal, transverse and torsional modes. Analytical and finite-element models show maximum tension near GEO, with natural pendulum periods of 6 h to 12 h for whole-system swing and higher harmonics excited by climber passage [16]. Active damping—via counterweight shuttling, climber scheduling, or base platform repositioning—can suppress resonant build-up [17]. Segmented designs add local pendula at each node, but stability analyses indicate that small perturbations remain bounded if the centre-of-mass stays above GEO [18].

2.4 Deployment Logistics

Edwards' NIAC concept deploys a seed ribbon from GEO downward, then thickens it through successive reinforcement climbs [1]. Segmented proposals extend this bootstrap with stage-wise insertion of prefabricated sections: GEO $\rightarrow$ LEO $\rightarrow$ stratosphere, while a counterweight (or extended upper tether) is simultaneously unspooled outwards to keep the combined centre-of-mass above GEO [11, 8]. Orbital-dynamics simulations confirm that thruster station-keeping during the critical hand-off phase is within current electric-propulsion capability.

2.5 Safety and Risk-Mitigation Frameworks

Comprehensive risk assessments consider cable severance, climber malfunction, debris and micrometeoroid impacts, severe weather and lightning, radiation exposure, and deliberate attack. Redundant multi-strand ribbons, continuous robotic inspection, and rapid module replacement are recurring mitigation strategies [12, 8]. Segment isolation limits the propagation of a fracture, while a jettisonable counterweight can force the tether to recoil harmlessly outward in a worst-case break scenario.

2.6 Economic and Programmatic Considerations

Cost estimates span \$10–100B (2025USD) for first-of-a-kind systems, with long-term launch prices projected to fall below \$300 kg^{-1} [1, 13]. Analysts argue that once a single elevator is operational, material hauled up the ribbon can seed additional tethers, compounding capacity and lowering marginal cost. Business-case models highlight cargo delivery, space-based solar-power infrastructure, asteroid-mined resources, and tourism as primary revenue streams.

Research gap—Most prior work optimises either material micro-structure or macro-scale dynamics in isolation. Few studies quantify the *system-level* interaction between modular geometry, joint reliability, repair logistics, and economic pay-off. The present paper addresses that gap by integrating a modular CNT tether design with coupled static–dynamic analysis and a deployment/maintenance model.

3 Modular Tether Design

3.1 Orbital Mechanics and GEO Anchor Placement

The *geostationary anchor* is the kinematic fulcrum of an Earth-based space elevator. Its location—and hence every downstream design variable (taper ratio, counterweight mass, segment stresses)—is fixed by first principles of orbital mechanics.

(a) Geostationary Orbit Radius and Angular Rate

A satellite is geostationary when its orbital period equals Earth's sidereal rotation period, $T_\oplus = 86,164.1\,\mathrm{s}$. Setting the gravitational force equal to the required centripetal force yields:

$$\frac{GM_\oplus}{r_{\mathrm{GEO}}^2} = \omega_\oplus^2 r_{\mathrm{GEO}} \quad \Longrightarrow \quad r_{\mathrm{GEO}} = \left(\frac{GM_\oplus}{\omega_\oplus^2}\right)^{1/3}, \tag{1}$$

where:

- $GM_\oplus = 3.986 \times 10^{14}\,\mathrm{m^3\,s^{-2}}$ is Earth's gravitational parameter,
- $\omega_\oplus = \frac{2\pi}{T_\oplus} = 7.292 \times 10^{-5}\,\mathrm{rad/s}$ is Earth's angular velocity.

Evaluating this expression yields:

$$r_{\mathrm{GEO}} = 42,164.2\,\mathrm{km} \quad \Longrightarrow \quad h_{\mathrm{GEO}} = r_{\mathrm{GEO}} - R_\oplus \approx 35,786\,\mathrm{km}$$

with $R_\oplus = 6,378.1\,\mathrm{km}$. The orbital velocity at GEO is then:

$$v_{\mathrm{GEO}} = \omega_\oplus r_{\mathrm{GEO}} \approx 3.07\,\mathrm{km/s}.$$

These constants define the anchor coordinate for all tension-balance and dynamics calculations [19, 20].

(b) Centrifugal–Gravitational Balance Along the Tether

For a tether element at geocentric radius r, the net radial acceleration is:

$$a_{\text{net}}(r) = \omega_{\oplus}^2 r - \frac{GM_{\oplus}}{r^2}.$$

- Below GEO: $a_{\text{net}} < 0$ (net force pulls inward),
- Above GEO: $a_{\text{net}} > 0$ (centrifugal force dominates).

The tether must extend beyond GEO to maintain pre-tension via centrifugal force. Practically, the counterweight is placed around 100–110,000 km from Earth so that the center of mass r_{CM} lies approximately 500 km above GEO, ensuring passive stability against lateral perturbations [21].

(c) Implications for a Modular Architecture

1. **Segment definition:** Each modular segment must reference its position r_i relative to GEO, as axial load reverses direction across GEO.
2. **Joint forces:** Maximum tensile stress occurs near r_{GEO}, requiring segment joints in this region to offer near-ideal load transfer.
3. **Deployment sequence:** During bootstrap, the seed ribbon is extended downward and upward from GEO. A segmented tether allows prefabricated modules to be attached on the upward leg, easing logistics and reducing spool size.

(d) Boundary Conditions for Tension Modelling

Let $y = r - R_{\oplus}$ denote altitude from Earth's surface. The axial tension $T(y)$ satisfies:

$$\frac{dT}{dy} = \mu(y)\, a_{\text{net}}(y), \tag{2}$$

subject to the boundary conditions:

$$T(0) = 0, \qquad T(L) = 0,$$

where $L \approx 100,000$ km is the total tether length. These zero-tension conditions arise from support at both ends—via base station and apex counterweight. Later sections will adapt these conditions to include joint compliance in segmented architectures.

This orbital mechanics framework sets the geometric and dynamic constraints under which all subsequent material, taper, and modular-joint calculations must operate.

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