Fisher Space Systems, LLC

Space Track Launch System
Proof of Concept

Addendum A: Tower Construction

by
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A1.0 Introduction

This addendum discusses a possible construction technique for the proof of concept tower. The proof of concept system will be a 25 km tall sub-scale model of a fully operational first generation system. The proof of concept system will demonstrate the launch of a second stage suborbital launch vehicle with separation from an overcarriage on a rotating ribbon.

Section A2.0 of the addendum discusses transportation of the support beam (SB) from the manufacturers site to the construction site. The 1.5 km SB will be the most difficult to transport with transportation getting easier for the 500 m construction beams (CBs). Section A3.0 of the addendum discusses the construction of the tower. A relatively smaller multi-beam construction tower is required to construct the larger multi-beam support tower. Section A4.0 of the addendum reviews the theory supporting the multi-beam construction tower. Section A5.0 of the addendum is the conclusion.

A2.0 Beam Transportation

At ground level there are 600, 1.5 km tall inflatable support beams. The 600 beams are divided into 4 clusters. Each cluster has 150 beams arranged in 3 rows of 50 beams. Each SB is 2.0 m in diameter and has a mass of about 10 metric tons. Specially designed 6-axle semi-trailers are used to transport the 1.5 km beam to a rail spur located near the manufactures site. Many states issue super load permits for such transport. For example, exempt super load blanket permits are permitted by the Transportation Code of Virginia.

At the rail spur, the 1.5 km SB is loaded onto a heavy capacity flatcar. A 1.5 km beam, 2.0 m in diameter, 0.75 mm thick wall thickness, and 10 ton mass just fits into a heavy capacity flatcar. Once a sufficient number of beams are loaded onto flatcars, the flatcars are moved to the main rail line and transported to a rail station near the construction site.

At the rail station, the flatcars are moved to a rail spur and transported to the construction site. The support beams are off loaded onto 6-axle semi-trailers and moved to the base of the tower at the construction site.

A3.0 Tower Construction

To build a 25 km multi-beam support tower for the proof of concept system, first build a 1.5 km multi-beam construction tower. The 1.5 km construction tower consist of 3 layers of 500 m construction beams for each layer. Each layer is connected together before construction begins on the next layer. The first layer starts with four construction beams, one for each cluster. Construction begins on all 4 beam clusters simultaneously.

At the construction site, the semi-trailer carrying the 500 m construction beam backs up to the support tower base (figure A1). The 500 m CB is divided into 100 m air cells. Each cell has its own air inlet and pressure gauge. The base flange of the CB is connected to the support tower base and an air line is connected to a distribution manifold. The first 100 m section of the construction beam is inflated. The CB is inflated at an angle of 0.1° because the tower SBs are titled in by 0.1° to help stabilize the tower during operation. As the CB inflates, it unfolds from the transportation container.

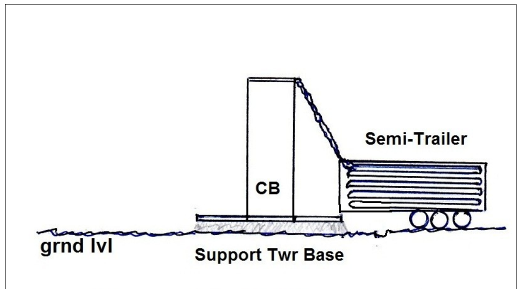

Figure A1. CB Transport

Once the first 100 m section of the construction beam is inflated, a climber ascends to the top (figure A2). The climber is a truss with ribbons hanging from support rails. The climber is stabilized by guy wires attached to the truss. When the climber reaches the top and is secured, the next 100 m section of the CB is inflated (figure A3). The climber ascends to the top of the second 100 m section and is secured. The procedure is repeated until the CB is fully inflated to 500 m. Once the construction beam is stabilized, a beam inspection, maintenance, and equipment repair robot (BIMERR) climbs the ribbon carrying a monorail section (figure A4), attaches it on top of the CB, and returns to ground level.

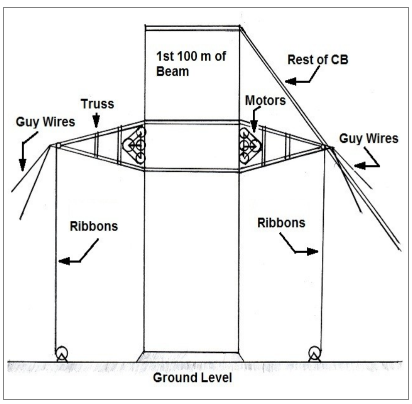

Figure A2. CB with Climber

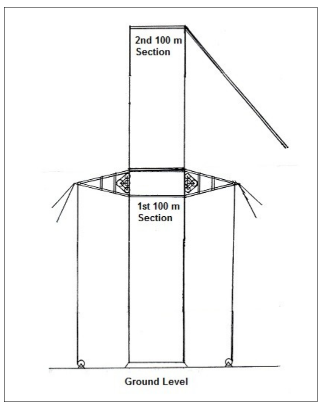

Figure A3. Second 100 m Section

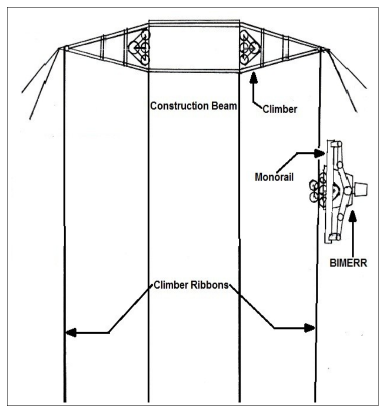

Figure A4. BIMERR with Monorail

Two BIMERRs bring up a rail car (figure A5) and place it on the monorail section (figure A6). The rail car is a truss with ribbons attached to each side, similar to the climber. The BIMERRs on the climber ribbons return to ground level, grab another 500 m CB with a monorail section attached and guide it into position while the CB is inflated (figure A7). Once inflated, the CB is secured and the monorail section is attached to the monorail section on the first CB (figure A8). The rail car moves over to the new CB and BIMERRs bring up another CB with a monorail section attached. The rail car is designed to travel along the monorail supporting assembly of the first 500 m of the multi-beam construction tower. All 4 clusters are completed at the same time and the monorail sections are connected together.

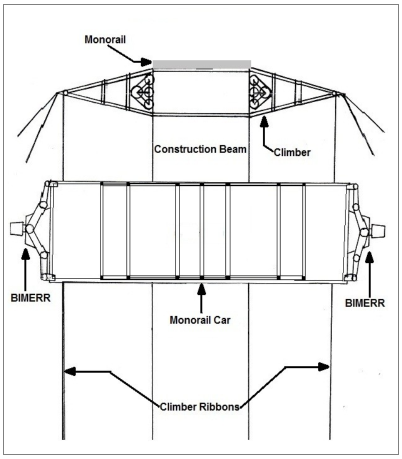

Figure A5. BIMERRs & Rail Car

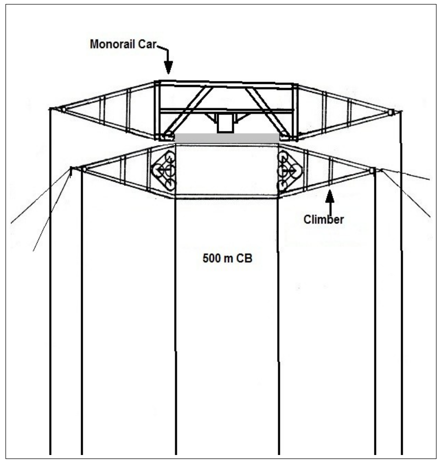

Figure A6. Rail Car

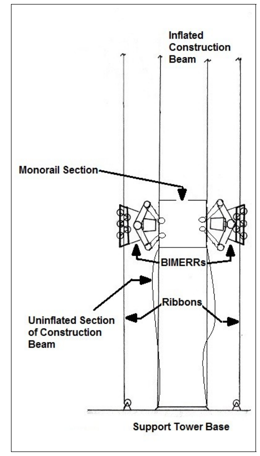

Figure A7. Next CB Inflation

Now that the monorail sections are connected, the area moment of inertia and the critical buckling load increase by six orders of magnitude over that of a single construction beam. The construction begins on the next 500 m level of the multi-beam construction tower.

With the climber attached to the monorail, the 500 m section of the original CB is deflated. BIMERRs climb up the rail car ribbons, temporarily remove the guy wires and ribbons from the climber, and the climber rotates with the 500 m section of the CB still attached (figure A9). The guy wires and ribbons are reattached and the climber is secured. A 500 m CB is inflated to fill the gap vacated by the original CB. The first 100 m section of the original CB is inflated, the climber ascends and is secured (figure A10), the next 100 m section is inflated, the climber ascends and is secured, and so on until all 5 of the 100 m sections are inflated and the climber is secured. BIMERRs bring up the monorail section and the rail car and construction begins on the 2nd 500 m level of the multi-beam construction tower. The process is repeated for the 3rd 500 m level. The monorail sections are connected, the area moment of inertia and the critical buckling load increase, and the 1.5 km multi-beam construction tower is now complete.

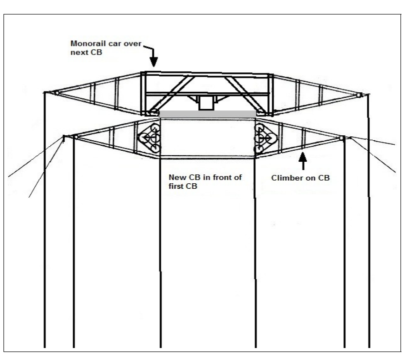

Figure A8. Monorail Car on CB

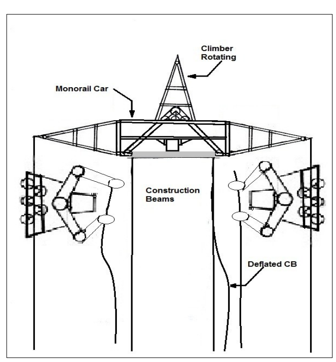

Figure A9. Climber Rotating

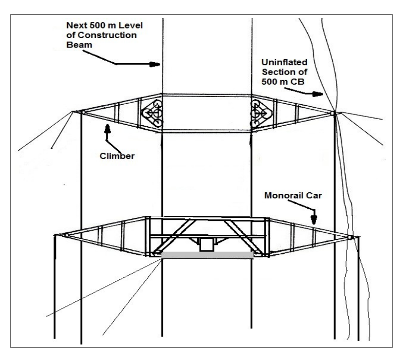

Figure A10. Next 500 m of CB

BIMERRs on the climber ribbons remove the rail car and return it to ground level. The BIMERRs bring up and assemble the first interface ring (IR) sections of the 1st level IR. The IR sections are attached to the monorail section on top of the CB (figure A11). The IR sections have guide rails attached. The rails support ribbons for regular maintenance, repair and replacement of the support tower. Each BIMERR returns to ground level, grabs the top flange of a support beam (SB), and guides the SB into place while it is inflated. The SBs are attached to the inner and outer circumference of the IR (figure A12).

The BIMERRs bring up ribbons and attach them to the IR section guide rails. Now that the ribbons for regular maintenance, repair and replacement are installed, BIMERRs on each side of the CBs continue adding IR sections and SBs until the inner and outer circumference of 100 SBs are installed on the cluster. There are four clusters each with 100 beams. The clusters are attached together. Permanent guy wires are attached to the completed interface ring. The interface ring at 1.5 km is now complete and BIMERRs remove the CBs and begin installing the remaining 200 support beams on the center row.

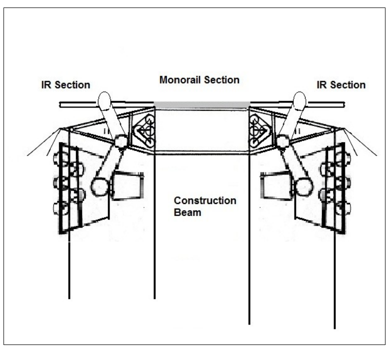

Figure A11. IR Sections

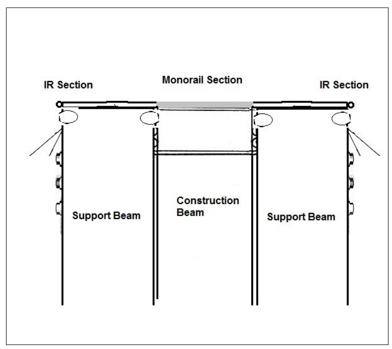

Figure A12. SB/IR Connection

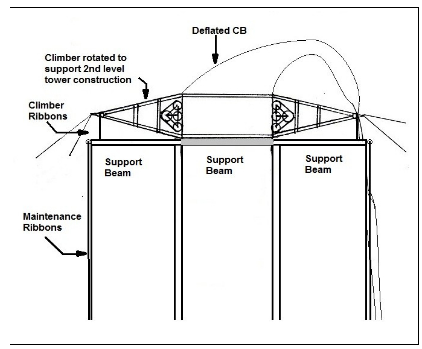

Figure A13. First Level IR

While the remaining SBs are being installed on the first 1.5 km level of the tower, construction of the second 1.5 km level of the tower begins. The climber attaches to the IR section. The BIMERRs descend to the 1st level CB connection at 500 m. The 500 m section of CB is deflated and lowered to ground level by one of the BIMERRs. The other BIMMER disconnects the monorail and lowers it to ground level. They return to the 2nd level CB and also, lower it and monorail section to ground level. BIMERRs on the maintenance ribbons temporarily disconnect the guy wires and ribbons from the climber, the climber rotates, and the guy wires and ribbons are reconnected (figure A13). A 1.5 km SB is inflated to fill the spot vacated by the CB and to support the 3, 500 m sections of the CB during construction of the 2nd 1.5 km level of the support tower.

The remaining 15 levels of the proof of concept support tower are constructed in a similar fashion. BIMERRs from the lower levels transport and transfer the climbers, 500 m CBs, monorail sections, rail cars, and 1.5 km support beams to the BIMERRs located on the upper levels. When all of the levels are constructed, BIMERRs carry 25 m sections of the torque buffer to the top and assemble the torque buffer. After the torque buffer is assembled, BIMERRs carry the elevator support structure to the top, the structure is assembled, and elevator ribbons are attached.

Up to this point, construction of the tower is done using the BIMERRs. The BIMERRs are remotely operated by a construction crew located at ground level. The BIMERRs have some autonomy (e.g. climbing up and down the ribbons and moving along the circumference using the rails) but are remotely operated for the construction parts. With the addition of the elevator support structure, ribbons, and elevators, construction crews in exoskeletons can work on and complete the construction of the proof of concept tower. With the proof of concept tower, the equipment, techniques, and procedures can be developed resulting in a cadre of near space and low earth orbit construction crews.

The elevators and BIMERRs transport construction material to the top and the transfer station is completed. The rotating truss and ribbons are installed and proof of concept begins.

A4.0 Construction Beam Theory

There are 4 major issues that need to be address in the beam theory section. First, the beam moment during inflation of the 500 m CB. The maximum lateral force during inflation occurs when the first 300 m is inflated with 200 m left to inflate. The beam moment has to be greater than that introduced by the deflated portion of the beam. Second, the maximum payload capacity of the 500 m beam has to be greater than the load. Third, the 500 m CB is titled in by 0.1°. The lateral force on the beam due to the mass of the beam, the mass of the fill gas, and the load has to be offset by the guy wires. Finally, the critical buckling load of the beam also needs to be greater than the load. The section begins by first addressing the beam moment.

For an inflated construction beam, the moment is given by (R.K. Seth, B.M. Quine, and Z.H. Zhu, 2009),

$$Beam\ Moment = 0.4\pi\sigma_w tR^2$$

where σ_w is the working tensile strength for Kevlar (Kevlar, 2012) equal to 1.2 x 10^9 N/m^2 (S.F.= 3), t is the thickness of the beam fabric equal to 2.0 mm, and R is the radius of the beam equal to 1.0 m. Inserting the variables gives the beam moment equal to 3.0 x 10^6 N-m.

The greatest lateral force on the CB occurs when the beam is inflated to 300 m with the climber at 200 m. The hanging mass of the deflated beam is about 3.6 x 10^3 kg or a load of 35 kN. The deflated beam drapes over the climber ribbons making an angle of approximately 1.2° at the top. This gives a lateral force of 710 N and a moment of 7.1 kN-m, well below the moment of the construction beam.

The estimated load at the top of the 500 m CB is 1.2 x 10^4 N. This load consist of the climber with ribbons, two BIMERRs, a monorail, and a rail car with ribbons. The maximum payload capacity of the 500 CB construction beam is given by (R.K. Seth, B.M. Quine, and Z.H. Zhu, 2009),

$$MPC = \frac{\sigma_u}{(\frac{R}{t})} - \frac{(2H\rho g)}{(\frac{R}{t})} - H\rho_g' g$$

where σ_u is the ultimate tensile strength of Kevlar equal to 3.6 x 10^9 N/m^2, R is the radius of the beam, t is the thickness, H is the length equal to 500 m, ρ is the density of Kevlar equal to 1440 kg/m^3, g is equal to 9.81 m/s^2. and ρ'_g is given by,

$$\rho'_g = \frac{\mu\sigma_u}{R_g T(\frac{R}{t})}$$

where μ is the molecular weight of air equal to 28.96 x 10^{-3} kg/mol, R_g is the gas constant equal to 8.314 J/K-mol, and T is the temperature at ground level equal to 293 K. Inserting the variables gives the air density at 85.6 kg/m^3 and the maximum payload capacity for the 500 m CB equal to 6.8 x 10^6 N/m^2. The surface area at the top of the CB is about 3.14 m^2. Therefore, the maximum load is 2.1 x 10^7 N. The maximum load capacity is well above the load of 1.2 x 10^4 N represented by the climber, BIMERRs, monorail, and rail car.

The CB is tilted in by 0.1^o because the support beams on the proof of concept tower are titled in by 0.1^o. The tilt is necessary to stabilized the tower and to make room for the increase number of beams (resulting in an increase in area moment of inertia and critical load) as the tower load increases. When the CB is fully inflated the load at the top is 6.0 x 10^5 N. This results in a lateral force of about 1.0 kN. To offset this force, a guy wire at an angle of 30^o must provide a force of 2.0 kN. Spectra 2000® fiber (Spectra®, 2013) has a working tensile strength of about 1.1 GPa (S.F. = 3). The area required is approximately 2.0 x 10^{-6} m^2 and with a mass density of 970 kg/m^3 and a length of 577 m, the mass of the guy wire is about 1.0 kg.

The critical buckling load for the 500 m CB is given by (Seth, 2010),

$$P_{cr} = \frac{\pi^2 E' I}{L_e^2}$$

where E' is the effective modulus of Kevlar equal to 131 x 10^9 N/m^2 and L_e is the length of the inflated beam equal to 500 m. It is important to note that the effective modulus is equal to the material modulus at a certain minimum pressure and increases with an increase in pressure (Seth, 2010). More research is required to establish this relationship. At present, E' will be set equal to the material modulus.

The area moment of inertia, I, for the 500 m CB is given by,

$$I = \pi R^3 t$$

and is equal to 6.28 x 10^{-3} m^4. As such, the critical buckling load for a single CB is about 3.25 x 10^4 N. Recall, the load due to the climber, BIMERRs, monorail, and rail car is approximately 1.2 x 10^4 N. It is because of the critical buckling load, that the maximum height of the CB is set at 500 m.

Also recall, that 4 construction beams, one for each cluster, are inflated. Each CB has at the top a climber, two BIMERRs, monorail, and rail car. The thickness of the CB is 2.0 mm to handle the extra stress produced by the climbers. The remaining 49 construction beams on this cluster need only be 0.75 mm thick because they will be guided by BIMERRs while being inflated. The thinner beam has a critical buckling load of 1.2 x 10^4 N. The load produced by the monorail, rail car, and BIMERRs is 1.1 x 10^4 N. Note that there is no climber on the thinner CBs.

As the 500 m CBs are inflated, each with a monorail section on top, the rail car moves over to provide support for the BIMERRs while they are guiding the next CB into position. As the CBs become inflated the area moment of inertia increases. When all beams are inflated and the monorails are connected, the area moment of inertia for the multi-beam structure is given by (R.K. Seth, B.M. Quine, and Z.H. Zhu, 2009),

$$I = N\left(\pi R t \left(R^2 + r^2\right)\right)$$

where N is the number of inflated beams equal to 200 and r is the radius at the base of the structure equal to about 62 m. Inserting the variables gives the area moment of inertia equal to 1.8 x 10^3 m^4 and the critical load equal to 9.3 x 10^9 N. The area moment of inertia and the critical load are about 6 orders of magnitude greater than that of a single beam.

When the second level of the multi-beam construction tower is completed, the load on the first level consist of 200 inflated CBs, a completed monorail, four rail cars, four climbers, eight BIMERRs, ribbons, and guy wires. The load is approximately 1.0 x 10^9 N. When the third level of the multi-beam tower is completed the load on the first level is 2.0 x 10^9 N. The completed interface ring on the 3^{rd} level adds and additional load of 4.0 x 10^6 N. This is well below the critical buckling load of 9.3 x 10^9 N.

A5.0 Conclusion

The proof of concept system will be a 25 km tall sub-scale model of a fully operational first generation system. The proof of concept system will demonstrate the viability of an all electric first stage launch system. It will demonstrate the launch of a second stage suborbital launch vehicle with separation from an overcarriage and the mitigation of the shock wave in the ribbon produced during launch.

Construction of the multi-beam tower will start at ground level and rise to 25 km one level at a time. A specially designed multi-beam construction tower consisting of 3 levels of 500 m construction beams will assemble the first 1.5 km level of the tower. The construction beams will be deflated and moved to the second 1.5 km level. The beams are re-inflated and the second level is completed. Beam inspection, maintenance, and equipment repair robots (BIMERRs) will guide the beams into position and assemble the monorails and interface rings. The process continues until all 16, 1.5 km levels are completed. Construction engineers in exoskeletons will construct the transfer station and rotating truss. Once the ribbons and counterweights are installed, proof of concept begins.

References

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9
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