Payload Design for the Space Elevator Climber

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It is feasible, with present-day or soon-to-be available technology, to build a 20-tonne space elevator climber with room for 10 tonnes of payload. The type of payload will require modifications to the climber design and affect the stresses in the climber and in the space elevator tether. An iterative, finite element analysis was undertaken to study these stresses and to provide a first conceptual design of a payload support structure. The example of liquid oxygen transport to orbit was chosen. Unexpected stresses due to off-center payloads, uneven compressive forces due to overhung payload mass and unequal tensions in the tether were uncovered and solutions for alleviating these stresses were incorporated into the final design. Though the design for the support of liquid oxygen tanks was specialized for that particular payload, a similar design could be used for more general cargo and might resemble that used for intermodal freight containers.

Keywords: Space Elevator, Engineering, Design, Finite Element Analysis

1 INTRODUCTION

The first detailed, conceptual design of a space elevator climber showed that a friction-based, 20-tonne climber could be built with currently available or soon-to-be available technology. This design was presented in a recent study report [1] of the International Space Elevator Consortium (ISEC). Previous climber designs [2, 3] have stated a percentage of the total climber mass devoted to payload, but none deal with the issues of how the payload would be supported, the mass of the support structure or how these structures would have to be altered for different types of payload.

Of the 20-tonne total mass of the ISEC climber, about 10 are available for carrying payload. The climber drive, frame, power distribution, cooling, braking, disconnect systems, electronics and so on, make up the remaining 10 tonnes. The actual payload support structures and their mass are dependent on the type of payload, so this was not included in the mass budget.

To get a better idea of what is required to carry payload, the example of cryogenic fuel transport was considered. Liquid oxygen (LOX) would be an early and particularly useful payload for the space elevator climber. Elon Musk gave an update on Starship in early 2022 in which he showed how much LOX Starship needs to get to Mars: 1200 tonnes of propellant, about 700 tonnes of which is LOX [4]. This plan includes low Earth orbit (LEO) refueling of Starships from tanker Starships.

A space elevator could create and supply a propellant depot at geostationary Earth orbit (GSO) to serve such major customers. At least two five-tonne tanks of LOX or fuel could be sent up the space elevator every day from each of three Galactic Harbours [5]. To provide this capability, a conceptual payload design and stress analysis was performed.

Other types of payload will require different designs and different masses. Each payload type will require a separate optimization of climber and payload support structures. It is also expected that technological improvements will positively affect these optimizations. For example, graphene could replace aluminum structures and higher-torque, lower-mass electric motors could be used in the climber drive. It is thus likely that the current 50% payload ratio could be significantly improved.

2 DESIGN SUMMARY OF THE 20-TONNE CLIMBER

The design of the climber depends on the characteristics of the tether, the kind of drive it uses, the strong materials available, traction technology and economic considerations.

The choice of tether material is critical; it is the most massive component of the space elevator and must support itself as well as the climber. Its surface friction influences the type of climber drive used and its tensile and shear strength place constraints upon the climber mass and wheel clamping forces. Currently, graphene is the prime candidate [6].

Many drive options are available, but a friction-based, opposed-wheel drive is probably the simplest and most technologically developed. It depends on high-torque electric motors which today are very near what is required for the climber. For this option to be effective, a mutual coefficient of friction between the climber wheels and the tether material of 0.1 is required.

Lightweight materials such as titanium for the wheels and

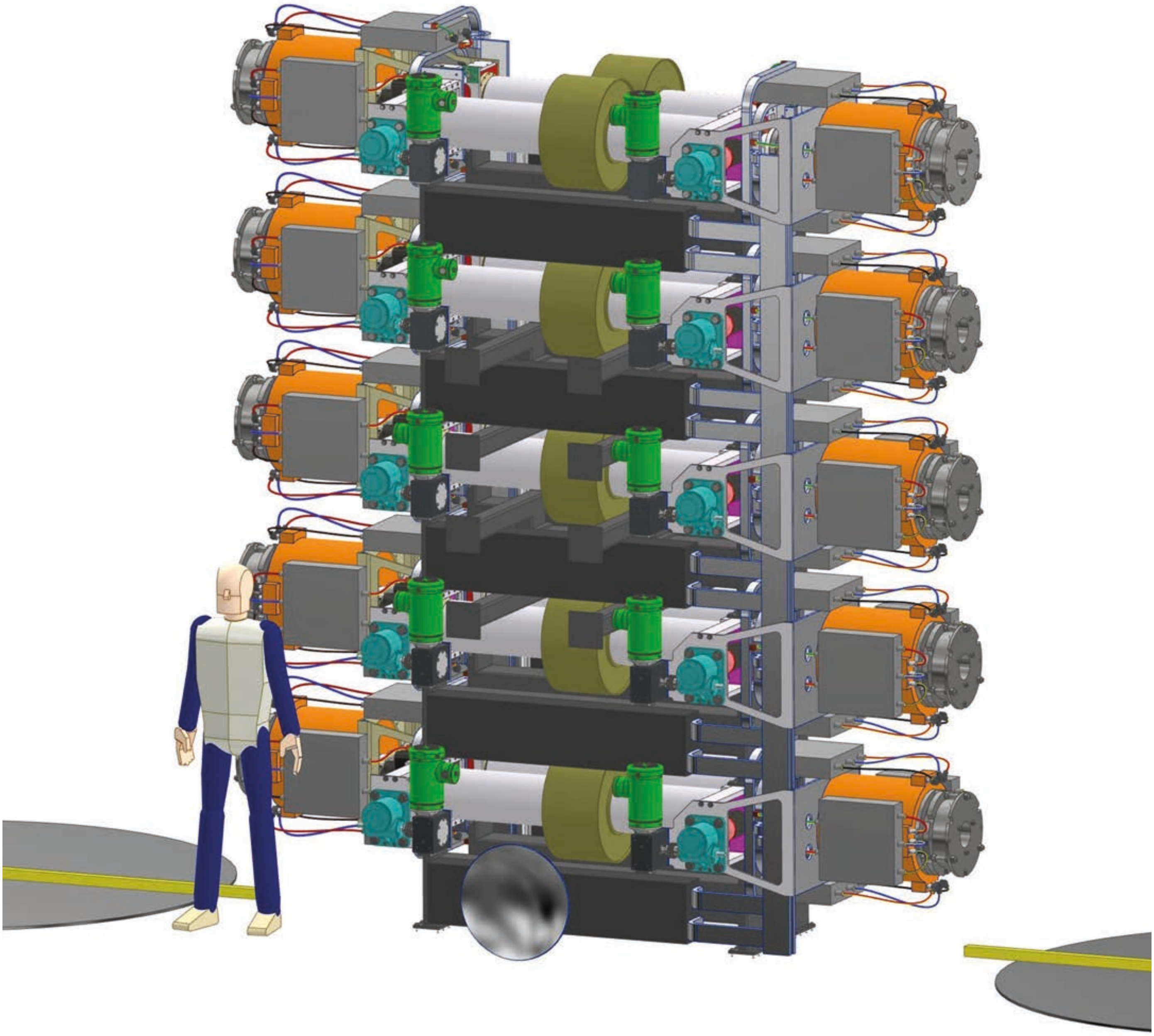

Fig.1 **Five-wheel-pair climber design. Opposed titanium wheels (olive) are mounted on axles (white) which are driven by electric motors (orange). Compression jacks (blue and green) force the wheels together and motor mounts (gray) are held together by an aluminum frame. Black bars represent emergency power batteries. Gray semi-circles at the bottom are parts of the power receiver panels.**

aluminum for the climber frame must be used to maximize payload. In future, graphene could be used for the climber frame as well as for the tether material.

Economic issues drive the payload and speed requirements. It was estimated that six space elevators, with daily launches of 20-tonne climbers, each with 14 tonne payloads to GSO, would be greatly superior to rockets delivering to the same orbit [7]. To achieve this schedule, the maximum speed of the climber would need to be 200 km/hr.

The design is also constrained by "climbability", a set of conditions which must be met in order for tether climbing to be possible. These are friction at the climber-tether interface, the temperature and combined stresses at the interface, the difference in tether tension above and below the climber (lift), motor torque, climber wheel radius, maximum available power and cooling. All of these are discussed in detail elsewhere [8].

Starting with the above choices and conditions, a conceptual design was developed for the climber. The design assumed that only existing technologies, or those expected to arrive soon, would be used. This rather conservative assumption was made for two reasons: design is easier when speculation about component specifications is not required, and a design using off-the-shelf technologies serves as a useful starting point for extrapolations into future technologies. In the end, a climber design using current technology might not meet the physical or economic needs of a space elevator, but with rapidly advancing technologies in the material and propulsion arenas, it is likely that a design using near future technologies will meet these requirements.

The final climber design is shown in Fig. 1. It consists of five pairs of opposed wheels which grip the tether between them.

Each titanium wheel is mounted on an axle which is driven directly by an electric motor. Compression jacks force the wheels together to provide friction. An aluminum frame binds the motor mounts together to provide rigid support.

About 4 MW of mechanical power is required to achieve the desired climber speed and mass. While the source of this power was not considered in the report, aluminum bus bars were included to distribute it. Power receiving panels were also included, but, as the method of power delivery was not specified, they served only as place holders for future designs. Dissipation of waste heat was handled by a large, cylindrical radiator encircling both the climber drive and the payload.

The climber was designed in separable halves, one half on each side of the tether. This allows easy attachment to the tether at the Earth port, as well as a way to jettison the halves in the event that the climber becomes stuck at altitude.

3 LIQUID OXYGEN PAYLOAD DESIGN

The concept for a LOX payload used carbon fiber reinforced polymer (CFRP) tanks attached to the climber frame by aluminum beam arms. The initial design is shown in Fig. 2. The mass of each tank was 242.6 kg and could contain 4,634 kg of LOX, for a total weight of 4,877 kg. The weight of insulation around the tanks was thought to be negligible. No other hardware was included.

This design immediately showed subtleties that had not been considered before. The climber as designed had a center of mass that was not on the tether. In that case, the climber would cause the tether to twist. Fig. 3 shows that if the tanks were identical, the arms that support the payload must be of different lengths in order to keep the center of mass on the tether.

3.1 Arm Stress and Deflection

A finite element analysis (FEA) of the CFRP arms was performed to see if the arms were strong enough to hold the five-tonne load at the end. This was a steady-state, static analysis in which the climber was hanging motionless on the tether and held up by friction alone.

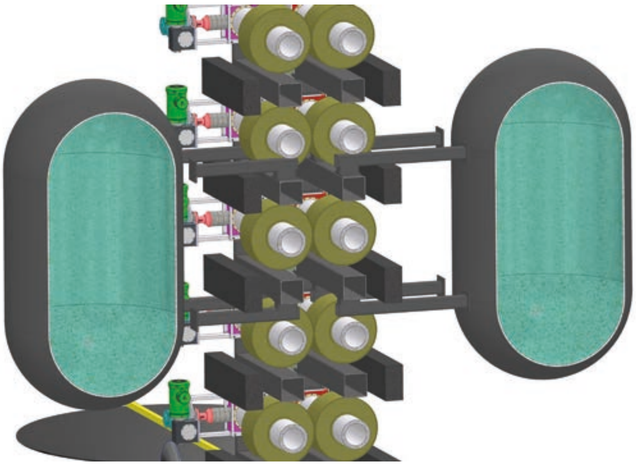

Fig.2 **LOX tanks (green interior) supported by cross beams attached to the climber frame.**

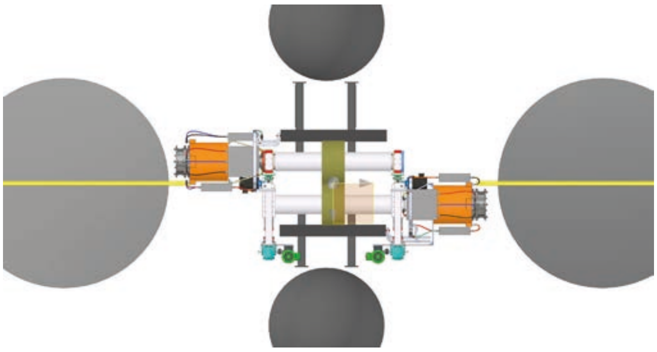

Fig.3 **View looking down on the climber showing payload tanks (dark gray) and support beams (dark gray) which have different lengths on one side of the climber than on the other. Large light gray circles represent the the power receiver panels.**

The results of the first four-arm analysis are shown in Fig. 4, with the stress map on the left and the deflection map on the right. The yield strength of CFRP is 300 MPa. The FEA showed a maximum stress of 1,537 MPa (222.9 ksi), well above the limit of the material, and a maximum deflection at the end of the

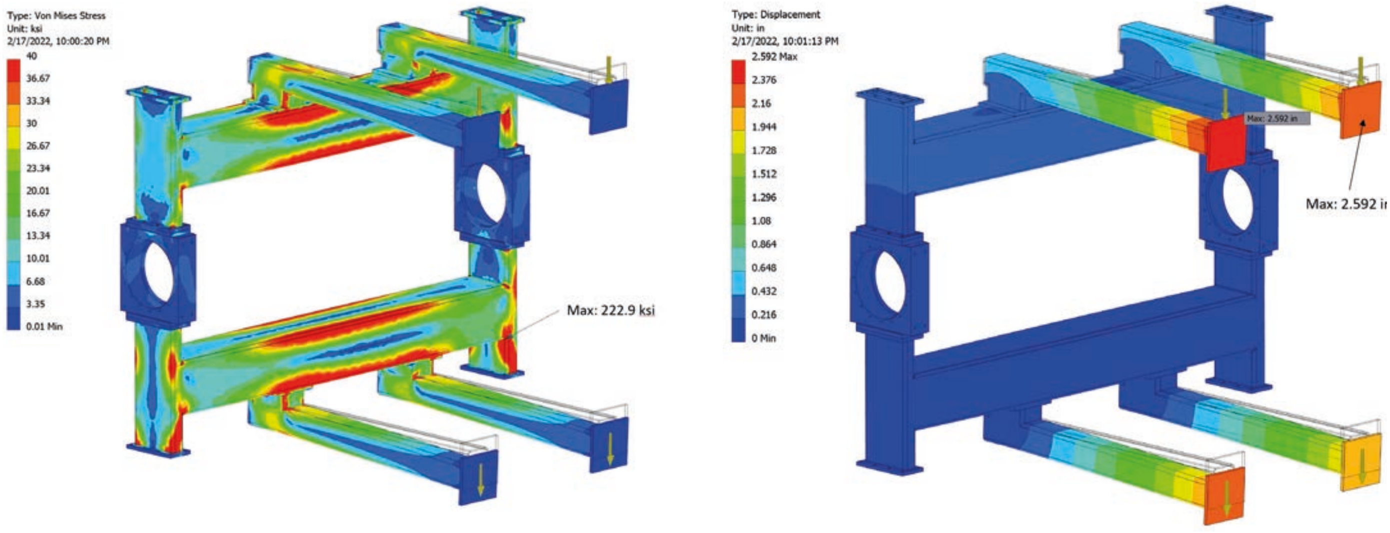

Fig.4 **Finite element analysis stress map (left) and deflection map (right) for the initial payload support design. Stress scale is in ksi (1 ksi = 6.89 MPa) and deflection scale is in inches.**

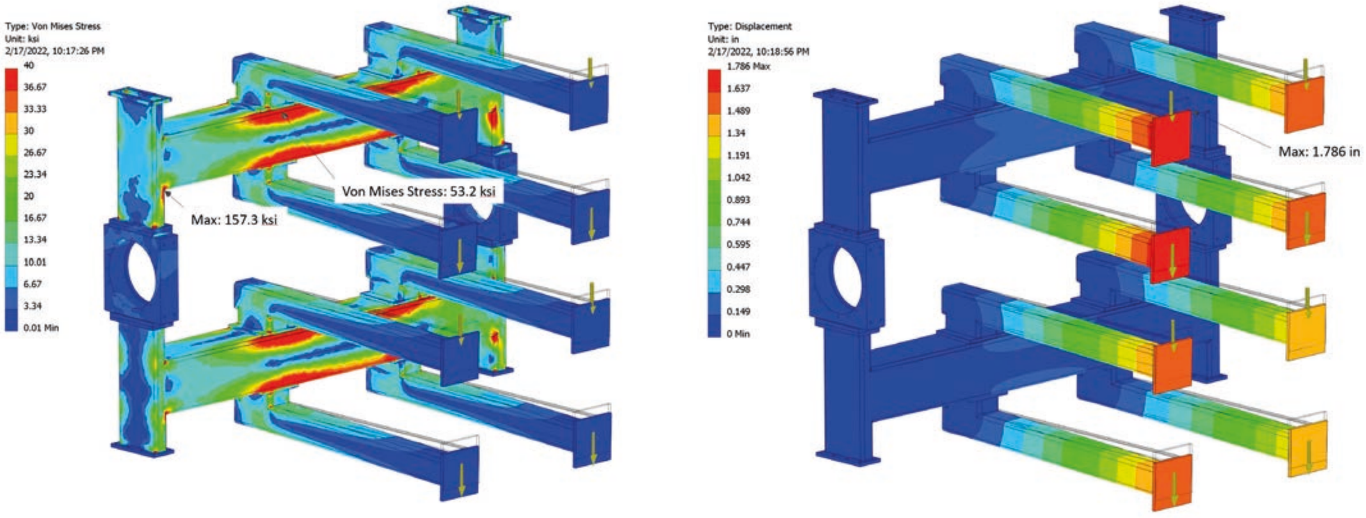

Fig.5 Finite element analysis stress map (left) and deflection map (right) for an eight-arm payload support design.

arms of 65.8 mm (2.59 inches) which was also too large. Thus, the payload arms were too small in cross section to carry the load, and their anchoring points on the climber structure were overstressed as well.

One of the most efficient ways to strengthen cantilevered beams is by increasing the height of the beam cross section. The stiffness of the beam is a cubic function of the height of the beam. Unfortunately, the space between the axles and structural interconnects was too narrow to increase the height of the arms. Increasing that height would mean adding extra weight to the whole climber. The answer was to add more arms to help distribute the load to the frame of the climber.

Fig. 5 shows the effect of doubling the number of support arms. The maximum stress was reduced from 1,537 MPa to 1,084 MPa, still well above the material limit, and the maximum deflection was reduced from 65.8 mm to 45.4 cm which was also still too large.

This was remedied by attaching shear panels to pairs of horizontal beams, effectively making a beam whose height is measured from the bottom surface of the lower arm to the top surface of the next higher arm. The stiffness was thus substantially increased.

Fig. 6 shows the effect of adding the shear panels. The horizontal beams were now stiff enough to move the high stress area into the smaller cross section vertical beams of the climber frame. However, the maximum stress of 505 MPa (73.3 ksi) was still too high for the CFRP. This area will need to be redesigned in future.

The total deflection came down to 17.8 mm. This might be acceptable, unless the stress is beyond the failure limit. One of the problems in working with CFRP is that the published values for its strength can vary by orders of magnitude. If the stress exceeds the yield of the material, then the deflection is just an artifact of the static linear analysis. More work needs to be done, especially in designing connections between CFRP structures that can be assembled and disassembled as needed.

3.2 Stresses on Wheels and Tether

Ideally, the stress from the payload will be evenly distributed over the wheel pairs. This is not the case in reality. The climber frame is not infinitely rigid and flexes under stress from the overhung load of the payload arms.

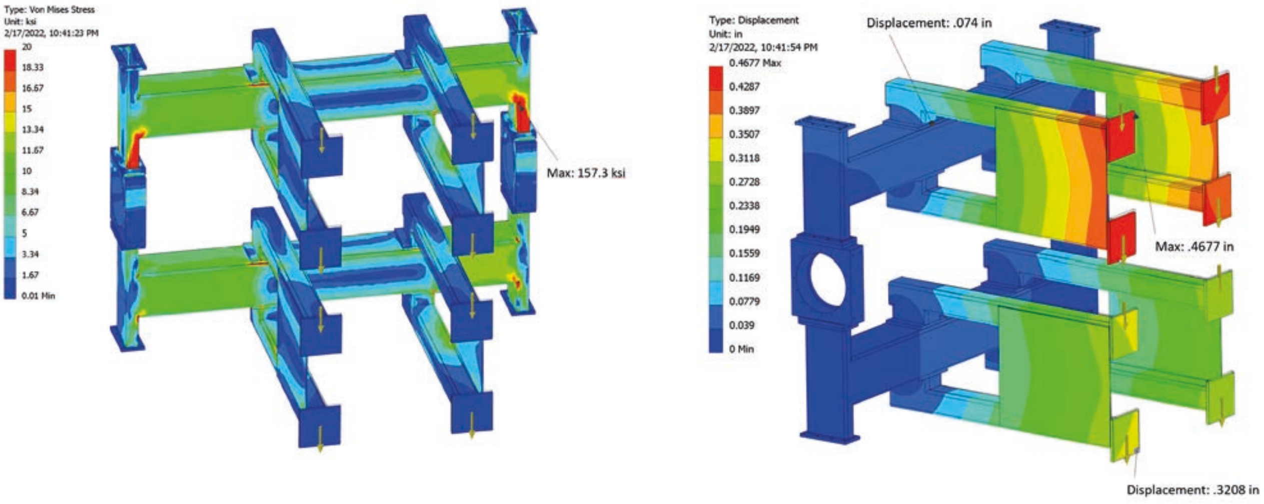

Fig.6 Stress map (left) and deflection map (right) for eight-arm design with pairs of arms stiffened by shear panels.

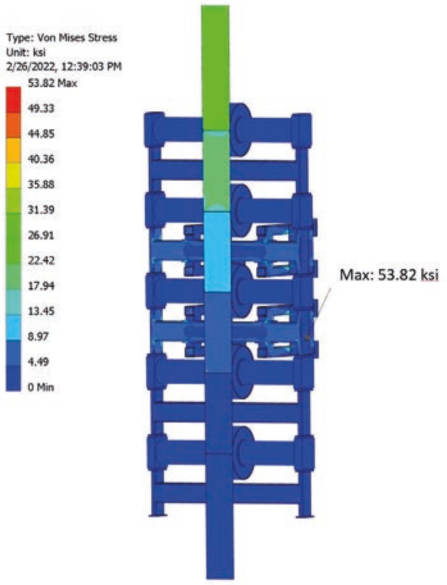

Fig.7 **Variation of the tether tension induced by the load from the payload arms. Variations in stress are seen near the wheel-tether contact patches.**

The tractive force that propels the climber is generated in the contact patch between the wheels and the tether. The contact patch arises from a temporary flattening of the drive wheels as they press against the tether and one another. Its area (about 1 m by 2 mm) depends on the compressive force that clamps the wheels together.

The FEA showed that as the frame flexes due to the payload support beams, the compression force of the wheels on the climber changed, causing the tractive force to vary along the tether. If the load were divided equally over five wheel pairs, the force would come to 12.13 kN, but the actual values were, from the bottom pair to the top, 14.15 kN, 12.71 kN, 7.68 kN, 12.71 kN and 13.41 kN. This variation in this force (84% from largest to smallest) means that the compression jacks which generate the tractive force will need to be adjusted for each wheel pair.

The torque required from each drive motor will also vary from wheel pair to wheel pair. The maximum design torque can no longer be determined by the average load, but rather by 1.17 times the average load, which is the greatest load divided by the average. A feedback mechanism based on wheel slippage would be required in order to adjust the compression force for slipping wheels.

These results assumed an incompressible tether. Adding a 1 mm thick graphene tether to the FEA allowed the payload stress on the tether to be calculated. Fig. 7 shows that an additional tension was introduced, increasing from the bottom of the climber to the top. Increased tether tension, combined with shear stress induced by the wheels, increased the combined stress in the tether which in turn would place tighter constraints on the tether material. This issue will require further study.

Fig. 8 shows the final conceptual design of the climber with two five-tonne LOX tanks attached. The finite element analysis performed for the long arms needs to be done for the short payload support arms on the left side of the picture. The mass of the longer arms and tank was 4,920 kg. The mass of the shorter arms and tank was 4,907 kg. The total climber plus payload mass came to 20,322 kg.

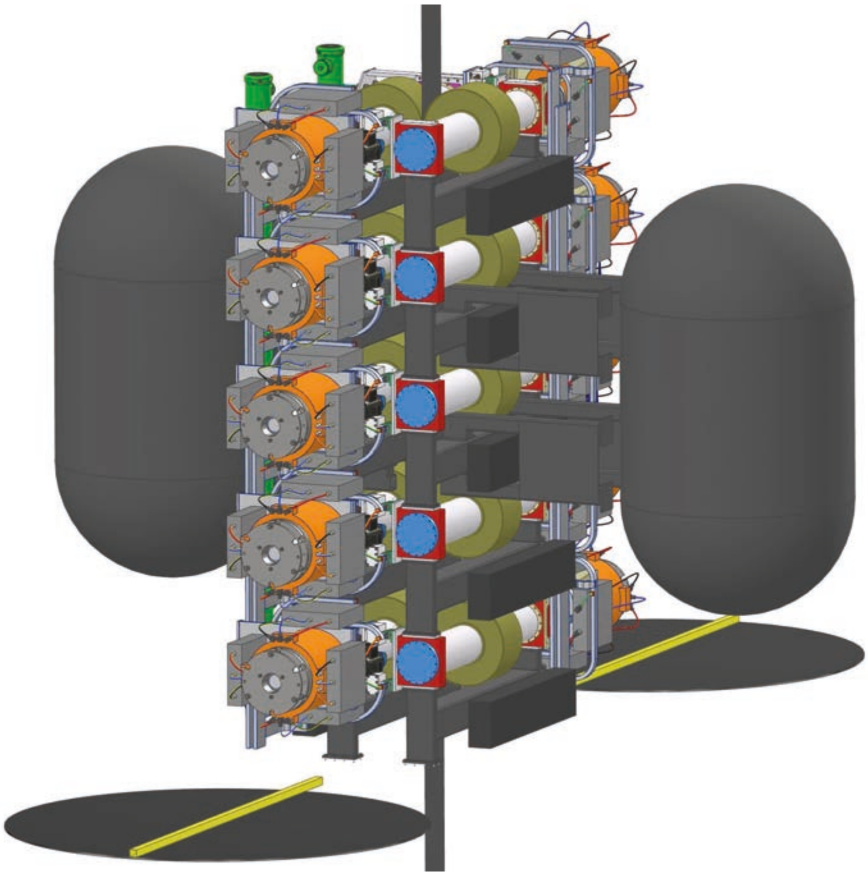

Fig.8 **Final conceptual design of climber, liquid payload tanks and support arms.**

4 IMPROVEMENTS AND OTHER PAYLOADS

The transportation of fuel by space elevator is a special case requiring a specific design solution to maximize mass efficiency. Large, bulky payloads, perhaps larger in dimension than the climber itself, would also require specialized designs integrated into the climber design.

A more standardized cargo would be a lighter version of intermodal freight containers. These would not be as mass efficient as specialized designs, but much more versatile in terms of cargo. As in the liquid fuel case, the 10-tonne payload would likely be split into two five-tonne containers, one on each side of the climber drive mechanism. This would allow the shortest possible support arms and permit the freight containers to fit inside the radiator panels which encircle the climber. A similar payload arm system would be used to fix the containers in place and transfer their weight to the climber frame. Many cargoes would not require pressurization; a simple cage open to space would suffice. This would reduce the support mass and simplify the design.

5 CONCLUSION

Given the feasibility of a 20-tonne space elevator climber with a 10-tonne payload, the next task was to examine the type of payload to be carried and how this would affect the climber design. A practical, early example is transporting liquid oxygen to orbit. An iterative design of the payload support structure using finite element analysis uncovered several subtleties.

The design of the drive train required that the payload support arms on one side of the climber be of different lengths to those on the other side. With identical LOX tanks, this requirement followed from the need to center the climber and payload mass on the tether. The overhung mass of the fuel tanks led to a flexing of the climber frame which in turn led to the uneven distribution of tractive force generated in the wheel pairs of the climber. Unequal tractive forces led to variable tensions in the tether itself, with consequences to the maximum material strength. Some of these issues could be dealt with by automatic control systems on the wheel pairs, but several items relating to material stress and weight transfer require further study in order to move the conceptual design to a detailed design.

A payload support structure similar to that for LOX transport could be used for generalized shipping modules, similar to today's intermodal freight containers but much lighter. Other, more specialized designs would be required for bulky payloads.

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