

A 5M LIGHTWEIGHT COMPOSITE ATMOSPHERIC TOWER FOR EXTREME ENVIRONMENTS

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This contribution presents a student project based on the conceptualization, designing and manufacturing of a lightweight composite tower for atmospheric measurements in extreme environments. The project was initiated by Asclepios, which aim to achieve analog space missions. Deployed on a celestial body, the measurement tower should resist low temperature, high wind loads and the weight of an astronaut climbing it to intervene on the atmospheric measurement equipment. A triangular truss tower was realized using glass fiber tubes. The connection of the tubes is based on 3D-printed PA-12 plastic connectors and the foundation consist of a sandwich panel. The tower is braced using Kevlar ropes connected with tensioners and carabiners. The entire tower weighs less than 30 kg. After proving the tower stability and structural integrity with full-scale mechanical experiments, it was mounted at the EPFL Sion to conduct field measurements and to monitor the tower's behavior under operational loading conditions.

Keywords: Space mission; Glass fiber; 3D-printed; Easily deployable; Economical.

Introduction

Any new space expedition begins with understanding the environment by establishing scientific outposts. One important aspect of the scientific research on a new planet is the study of its atmosphere, by collecting data such as temperature profiles, pressure, humidity rate, wind velocity, or air composition. These atmospheric measurements are collected using measuring devices fixed on a tower.

Designing such a tower leads to many challenges. The tower must suit the extreme environment of a celestial body, while being easily transported, built, and maintained. These towers are generally made of steel, but this project aimed to use the properties of composite materials to achieve the objective.

This is what this project was all about. The tower was designed in the frame of the Asclepios project, aiming to organize analogue space missions led by students, representing a short-term journey to an extraterrestrial body (like moon or mars). After a year of design phase, a prototype was successfully tested for 5 months (Dec-May) at Sion. Now, the project moves forward as the tower will be part of the 2022 Asclepios mission.

1. Requirements

The extreme environment and the context of a space mission imposed significant constraints on the conception. Space missions are characterized by a small number of astronauts, equipped with a spacesuit which includes gloves that restrain the mobility and precision. Thus, any screwing or small pieces difficult to handle must be avoided. As spacecraft are extremely tight, weight and compactness are primordial. Thus, it was set that the tower must be lighter than 100kg to be easily transportable.

Still, it is recommended for the Astronauts to be accustomed to the building process because of the extreme conditions in which they will build the tower, and because they could gain some precious time by already knowing the building steps. Therefore, an assembly guide had to be created to fully detail the process of the building of the tower.

The tower's primary function is to make atmospheric measurements. It is essential that the tower can carry the equipment that have an aggregated estimated weight of 40 kg. Besides, temperature and wind are also important loads. The tower should resist cold temperature around -20°C and a wind load of about 120 km/h.

2. Design

2.1 Structural concept

It was chosen to design a climbable truss tower. Three arguments pushed the decision. First, the ability to easily fix and repair all the devices by allowing one astronaut to climb. Thus, one device can be repaired without affecting the other measurements. Second, this shape grants very good stiffness and strength against lateral loads such as wind. Third, the tower can be built horizontally. All the operations can be done on the ground, easily and safely. Then, the frame is stiff enough to be lifted from a horizontal to a vertical position.

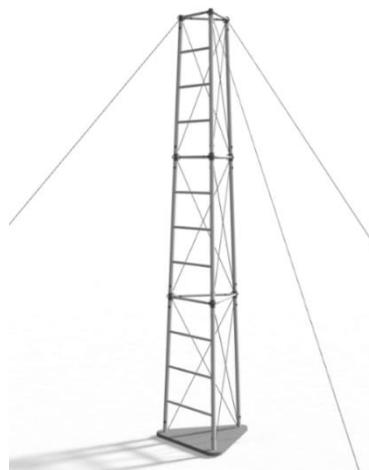


Figure 1. The triangular truss, with a ladder and bracings.

A triangular shape was chosen for its effectiveness. Adding more sides (square, pentagon) would increase the cost of the tower without any benefit on the stability. It was decided to incline the

columns by 2° degrees inward, to reduce the eccentricity of the vertical loads and enhance the stability. This inclination leads to sides of 80cm at the bottom and 44cm at the top, which is enough to climb. As shown in Figure 1, two intermediate horizontal triangles were added to create a rigid frame. Posts and horizontal bars are connected with 3D printed elements. On one side of the tower horizontal bars were placed to create a ladder and are directly inserted inside the vertical posts which are drilled, to avoid additional connection and facilitate the assembly. To make sure the bars stay in place, two collar clamps maintain the tube in its position. The two other sides of the tower were braced using Kevlar ropes. An external bracing, composed of three ropes anchored in the ground was added to improve the stability of the structure.

2.2 Materials

For transportation reasons, the tower should be lightweight while being 5m high. Besides that, the tower should resist cold conditions, humidity, rain, and snow. Considering this, composite materials were chosen due to their lightness, mechanical properties and durability. Composite tubes of carbon fibers or glass fibers were considered for the tower structure. While glass fiber tubes are five times cheaper than carbon fiber tubes, they have very good mechanical properties, satisfying the design recommendations, and therefore they were chosen for the tower manufacturing.

2.3 Clipping system

The frames were linked with 3D printed connections using Polyamide 12 (PA-12). Each connection is made of a node and four clips screwed in, as shown below in Figure 2. The clips were then inserted in the truss' tubes. The base of the tower was linked with the same clip system inserted into a sandwich panel to ensure the stability of the tower.



Figure 2. 3D-printed connection with a node and clips inserted in the tubes.

The design of these connections was based on a previous work [1]. The adaptation of these connections for this project includes handles for the bracing ropes and local reinforcement at the connections.

2.4 Bracing system

To resist lateral loads, the tower had to be braced. Two bracing systems were considered and appropriately designed in this work:

- An external bracing fixed on the top of the tower anchored in the ground to prevent any displacements of the top of the tower. It is particularly effective to stiffen the tower when someone is climbing.
- An internal bracing creating a lateral stiffness so that the structure behaves as a frame. This was realized by adding cables in the diagonals of the frame at each storey, for the two sides of the tower (the third one being already stiff with the introduction of ladder steps).

A 4 mm Kevlar rope was chosen as bracing material for its high tensile strength (5.8 kN – according to the product data sheet [2], lightweight and durability properties.

To reduce the number of cables, each one goes through two sides of the tower (see Figure 3) and are connected to the handles of the connections, as shown in Figure 4, mechanical tensioners connected with carabiners were used to easily tighten the system. This system allows one single person to tighten the cables by turning the screws.



Figure 3. Geometry of the cables



Figure 4. Tensioners connected to the handle

3. Design validation

3.1 Connection test

To have a better understanding of the tower performance, it is important to test the behavior of the connection itself, and especially investigate its rotational stiffness. The idea was to simulate the bending moment created in the connection while an astronaut walks on a ladder step. By doing so, the parameter of rotational stiffness of the connection could be implemented in a numerical model to have a precise definition of the tower's behavior.

A first test was realized by maintaining the connection with the ladder tube (small one) while pushing vertically on the post. The setup is shown on Figure 5. This simulates an instrument hung on the side or the wind pushing on a plate attached to the post. It results in a failure of the clip branch and of the connection simultaneously. As shown in Figure 7, the connection had a linear (elastic) behavior at the beginning of the loading. When the load of 0.2 kN was reached (it corresponds to a 60 km/h wind on a 30cm square plate), the graph continued in a plateau, that

means the deformation becomes plastic. This loading case is not really expected. The only force that could push against the posts is the wind, which is not a point force.

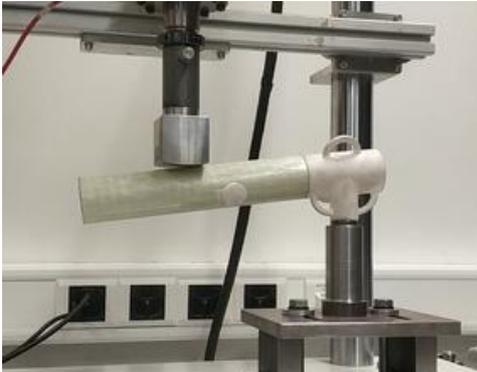


Figure 5: The setup in the post direction

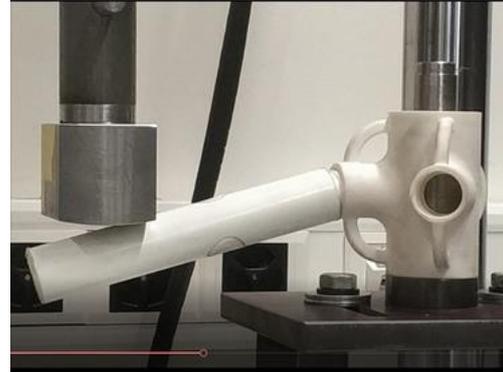


Figure 6: The screwing thread coming out.

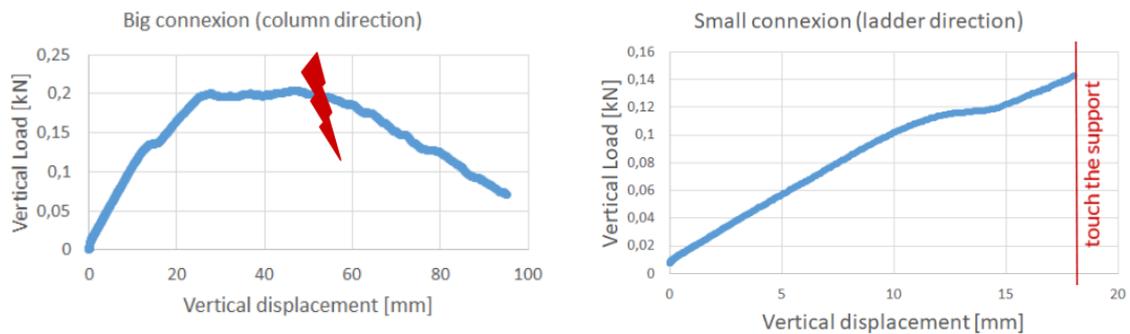


Figure 7: Tests results, in column and ladder direction, showing high connection deformability

The second test in the ladder direction was more representative of a real loading case. By applying a force on the ladder step, it simulates exactly what happens in the connection during the climbing of the astronaut. The behavior of the connection was completely different. As shown in the Figure 6, the screw part slipped little by little from the node. The connection did not carry any stress, but the two parts detached from each other. Unfortunately, the bar touched the support before failure, so the maximal deformation cannot be defined. However, this test led to the conclusion that the maximal deformation was high enough, in both loading cases, even if the forces applied were low. Therefore, the connection is considered as a perfect hinge. In order to increase the stiffness and reduce lateral displacement at the nodes, it could be possible to increase the length of the screw thread.

3.2 Full-scale testing

The aim of the full-scale testing was to simulate a real loading case, i.e., with the equipment fixed on the top and an astronaut climbing on it. This load was estimated to approximately 150kg (120kg for the equipped astronaut and 30kg for the measuring devices). Two tests were realized at the structural engineering platform (GIS-ENAC at the Ecole Polytechnique Fédérale de Lausanne, Switzerland), using a set of 17, 12kg iron bullions for the load application.

The first test simulated a vertical load centered at the top of the tower, representing the instruments and the astronaut. The setup consists of a belt fixed at one tube on the top supporting a box that can be filled with the iron bullion. The result is shown on Figure 8, with the following main observation: the more the compression in the post, the less the tension in the bracing. Indeed, the dynamometer was fixed to a cable that tend to de-stretch during the loading because the load was not exactly centered. If the dynamometer had been fixed on the opposite cable, a progressive tension would have been measured. Besides the pretension in the bracing cable that was applied manually with the tensioners corresponds to 12 kg, which is satisfying. All these observations ensure that the bracing system works.

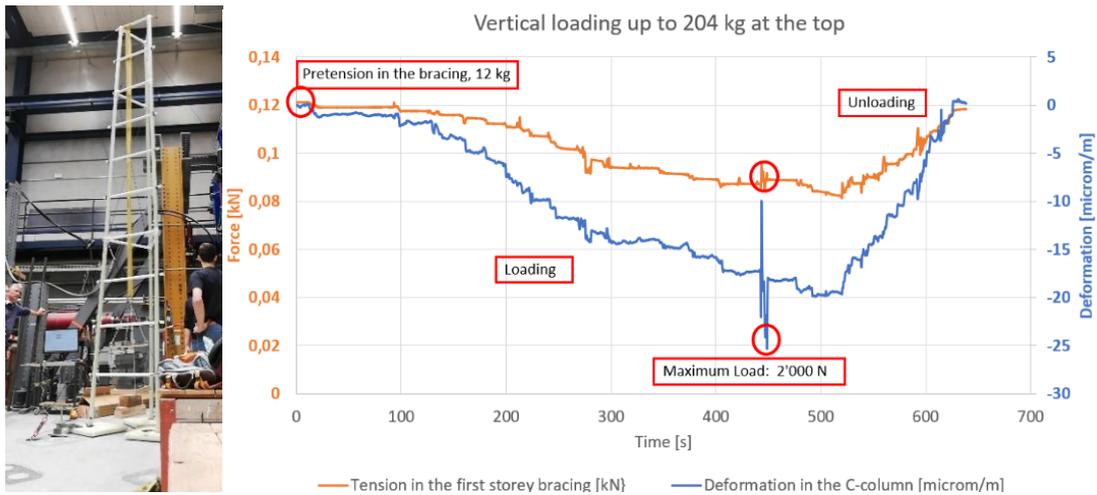


Figure 8. Vertical loading reaching 2'000 N without affecting the tower stability

The tower was loaded until 204 kg and did not show any structural weakness. The only part that was slightly damaged was the horizontal tube that supported the belt. A small deterioration of the tube shell appeared locally close to the node, which does not affect the tower stability. The goal of 150 kg was largely achieved.

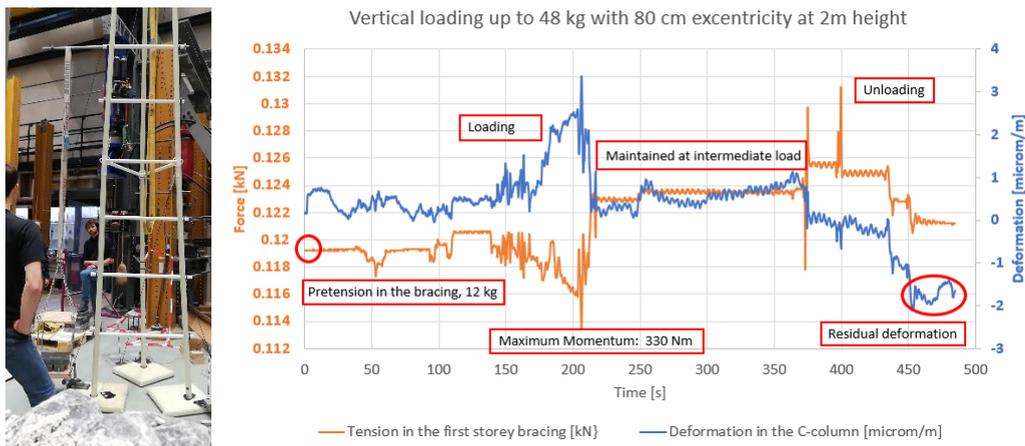


Figure 9. Eccentric vertical loading reaching 330 Nm momentum

The second loading was eccentric to create a moment in the tower, representing equipment fixed on the side. A steel rod was placed into the sixth step (2m high) and the belt was then fixed on it, with an excentricity of 80cm. The iron bullions were added one by one and then removed.

On Figure 9, the loading and unloading path can be observed. The noise in the results is probably due to the manipulation of the dynamometers during the experiments and the vibration induced by the loading using bullions.

4. Field testing

After successful tests in the lab, the tower was deployed in real conditions. It was installed the 7th of December 2021 in the garden of the ALPOLE center, Sion, with all the necessary instruments: an anemometer and an optical particle counter. The tower was carried easily by a van as it is very compact when dismantled and weighs less than 30kg. It took one hour for three people to build the tower from scratch. This time includes driving foundation's piles, connecting all the tubes together, bracing the tower, stretching cables, placing instruments, and connecting it to a self-built electrical power box. Then, people could climb the tower easily, that showed great stability, thanks to the addition of internal and external bracings systems.



Figure 10: An astronaut climbing the tower to intervene on the equipment

Monitoring was conducted for 5 months. During this period, the average temperature was -5°, with minimum at -10°C, while wind speed of 45 km/h was recorded. At the end of the winter, the tower did not show any malfunction or damage. Measures were taken without noise or disturbance.

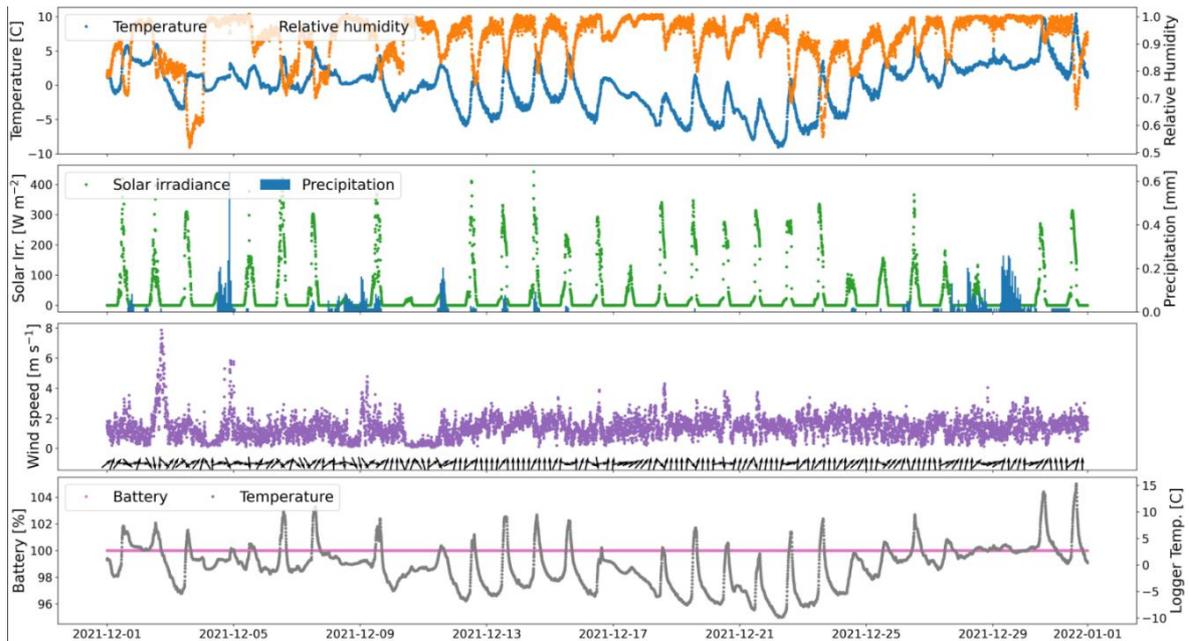


Figure 11 : Weather measurements in December 2021.

Conclusions

This project led to the design of a tower specifically suited to conduct atmospheric measurements in extreme environments. The tower has a low weight to height ratio, is easily buildable by a small crew of astronauts, avoiding any small pieces and the materials are durable. The tower has been easily and quickly built by three people, proving the efficiency of the assembly guide.

The experimental results showed that the tower can carry the atmospheric equipment as well as a man climbing up the ladder. Field testing validated the ability of the tower to operate in extreme environments over a long period (at very low temperatures during 5 months of winter in Sion in Switzerland). The precision of the measurements taken are promising.

To go further, it could be valuable to investigate on the fabrication of the tower to improve the process. Indeed, the tower is a unique prototype and was hand made in the structural engineering Experimental platform (GIS-ENAC at the Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland).

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