

T-Umbrella 2.0: Fabrication-Driven Redesign of an Inflatable Curved-Folding Pavilion

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Abstract

The relationship between curved-folding mechanisms and inflatable structures is an interesting field of investigation, as it enables very compact transport without requiring additional fold lines compared to solutions made from bendable plate materials. As it is known, bendable patches in a curved-folding mechanism can be interpreted as inflatable cylindrical tubes along rulings of an underlying surface. If the detailing follows a bespoke process, the fold angle between neighbouring rulings of two different patches can be set to a desired angle through inflation alone. The application of this strategy to a semi-discrete T-surface led to the development of a large-scale demonstrator at architectural scale. This so-called T-Umbrella pavilion is designed as a lightweight cantilevering structure, based on a single column surrounded with an inflatable seating structure covering a foundation. The development of this pavilion starting from the initial idea, over the first preliminary design and its iterations up to the layout of a preliminary test prototype in the scale 1:2 was already described in a paper presented at the IASS 2025. The 1:2 prototype served us as “learning structure” for the final design and manufacturing of the pavilion, which is the content of the paper at hand. In detail, we focus on the construction of the structure’s foundation and the fabrication-driven adaptation of the cutting pattern taking into account different strategies for the pressure distribution.

Keywords: structural origami, pavilion, pneumatic structures, curved folding, semi-discrete T-surface, fabrication.

1. Introduction

Using pressure-based methods in combination with foldable structures is an interesting combination as it enables the actuation of complex mechanisms with a simple technique. While both strategies have a long tradition in architecture, engineering and art, they are mostly seen as separate research fields without obvious overlaps. However, it is clear that both systems can be fabricated from flat sheet material, and both systems are actuated into a spatial three-dimensional shape. The digital tools available make the necessary knowledge for form generation and 2D development widely accessible [1, 2, 3, 4, 5] and applicable. Often the use of inflatables in this context is focused on the actuation of either rigid panels, as shown by [6], or bendable structures with curved fold lines [7]. The combination is especially interesting for mechanisms and applications at the metre scale, as the efficiency of inflatables, combined with the difficulties of large folding mechanisms in terms of required force and techniques, starts to correlate. The application of folding strategies not only for actuation but also as a holistic system, where the mechanism and the actuation are combined in one inflatable system of pouches, was introduced in [8]. The small

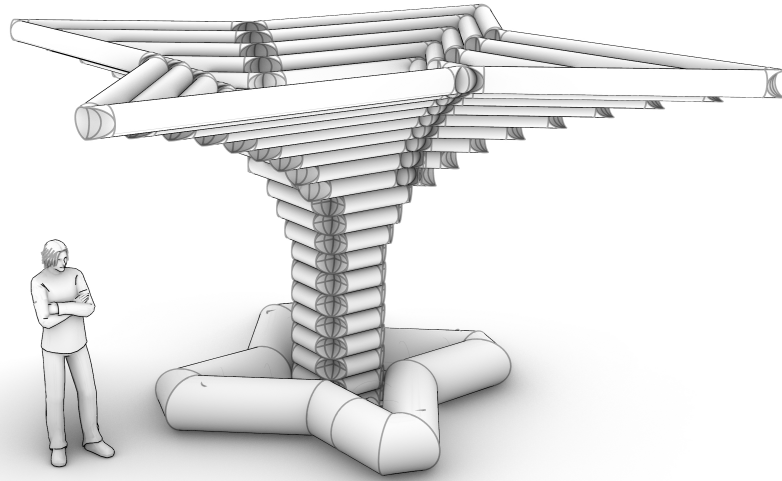


Figure 1: The T-Umbrella 2.0 as it will be exhibited at the IASS 2026.

demonstrators not only provided insight into the advantages of combining the systems, but also pointed to an expanding design space. Combining two deployable lightweight systems into one single approach helps to reduce the transportation size of an already compact foldable package to an even smaller package of material by solving the often critical actuation question on-site. Another benefit of this combination is that the actuation system is already integrated into the structural concept.

As the origin of the project and its first steps of development have been described in detail in an earlier publication [9], only a short introduction to the T-Umbrella is given here.

When the authors began to work on the T-Umbrella, the original question was the transportation size and weight of a complex foldable system for the IASS Pavilion exhibition in Mexico in 2025 [9]. The original idea was not only to develop a complex structure that consists of semi-discrete patches, with partly crossing fold lines and even reverse fold lines, but also to demonstrate that this complex mechanism can be fabricated flat and transported to a site as a small package or by package delivery, to be built up in less than a few hours. As the development required many different steps and techniques, a 1:2 prototype was fabricated to see if the estimates and fabrication approach was valid. The most challenging question was the fabrication of the foldable patches from connected inflatable pouches by a professional manufacturer [10]. In Section 2. the entire process, including the changes of the approach and therefore the cut patterns, is discussed in detail. Especially the development of folds and their related fabrication strategy should be highlighted here before referring to the 1:2 prototype in Section 3. that was used as a case study. As the learning structure has shown issues in the global stability caused by the cantilever and the relatively weak column in relation to the global weight, the stabilization of the structure will be discussed in detail in Section 4.. Contrary to the original concept of an inflatable stabilizing seating structure the redesign process of a stand-alone seating cushion is examined in Section 5.. These particular adaptations lead to the redesigned structure of the T-Umbrella 2.0 as sketched in Fig. 1.

2. Development of the cutting pattern

In this section we describe the development of the cutting pattern as an interplay between geometry constraints, production constraints and functional capability.

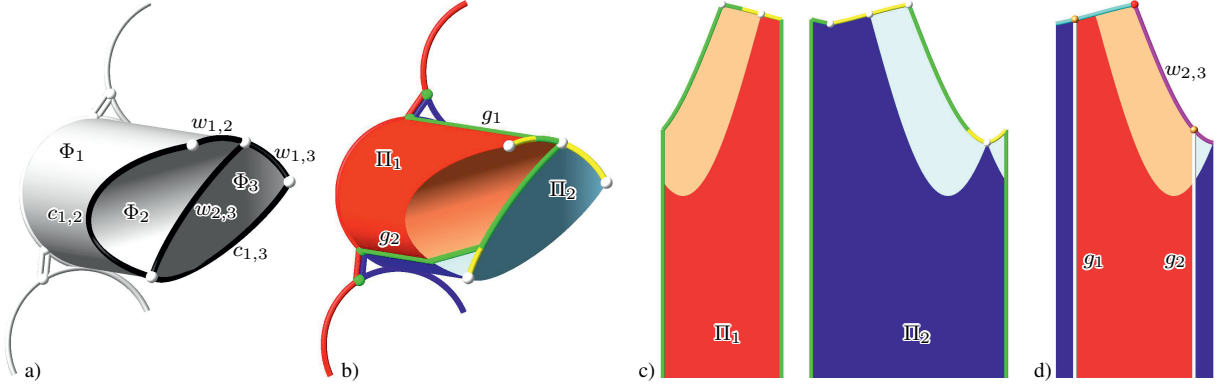


Figure 2: (a) Capping of a cylindrical pouch using mirror-reflection geometry. (b) Production from only two sheets of 2-sided TPU-laminated textile Π_1 (red) and Π_2 (blue). Welds between Π_1 and Π_2 are coloured in green and seams where the sheets are welded with themselves are displayed in yellow. (c) Development of the sheets Π_1 and Π_2 illustrated in (b). (d) Welding process: In the yellow points two weld lines ($g_1, w_{1,2}$ and $g_2, w_{2,3}$, respectively) are crossing and in the red point even three ($w_{1,2}, w_{1,3}, w_{2,3}$).

2.1. Initial strategy

Originally, it was planned to adopt the capping method of the cylindrical pouch presented in [8] for the curvature guided assembly of the cylindrical tubes of the T-Umbrella as explained in [9]. In the following we give a brief description of this modified capping, which is illustrated in Fig. 2a.

The capping of the cylindrical pouch Φ_1 should be constructed in a way that it is in contact with the adjacent pouch of the same row along the plane $\varepsilon_{1,2}$ which intersects Φ_1 along the elliptic section $c_{1,2}$. By reflecting Φ_1 in $\varepsilon_{1,2}$ we obtain Φ_2 . The capped pouch should be symmetrical with respect to a plane $\varepsilon_{2,3}$ which contains the cylinder axis a_1 of Φ_1 and is parallel to the plane spanned by the green rulings g_1 and g_2 (cf. Fig. 2b), which represent two rotation axes of the underlying flexible quad surface of T-hedral type. Therefore Φ_3 is obtained by reflecting Φ_2 in $\varepsilon_{2,3}$.

In [8, Fig. 6] the construction is explained in detail for the case where the intersection line of $\varepsilon_{1,2}$ and $\varepsilon_{2,3}$ is orthogonal to the axis a_1 . If this orthogonality condition is violated, then we get the situation illustrated in Fig. 2. In this case the cylinder Φ_i does not only intersect Φ_1 along the crease curve $c_{1,i}$ but also in a second elliptic curve $w_{1,i}$ for $i = 2, 3$. For small deviations from orthogonality the segments $w_{1,i}$ are very short and can be neglected as done in [8, Section 3.4]. But due to the cantilevering of the structure we are faced with larger deviations, where we have to deal with these additional welds $w_{1,i}$ increasing the complexity of the welding process, which is described next.

The main idea is to construct one segment of the T-Umbrella from welding only two large sheets of 2-sided TPU-laminated textile Π_1 and Π_2 (cf. Fig. 2bc). We take a closer look at the welding process of a single cylindrical pouch. First the two sheets have to be welded together along the rulings g_1 and g_2 . Then the resulting tube has to be flattened as illustrated in Fig. 2d, where the curved magenta weld $w_{2,3}$ can be produced. Finally, one has to fold in the red point to generate from the cyan curves the welds $w_{1,i}$.

Note that the slope of the plane $\varepsilon_{2,3}$ is different for each row of pouches, which results in a shape-change of the curved welds. Therefore a lot of welding tools have to be bent from a aluminium flat profile for an exact production. Moreover, in the extreme cantilevering part of the T-Umbrella the planes $\varepsilon_{2,3}$ have only less slope which result in a large distortion of the curves. Nevertheless, the points where seam lines are crossing each other can be done with special care, which is a time consuming task, they still remain error-prone areas. Therefore we decided to switch the method to the one described in the next section.

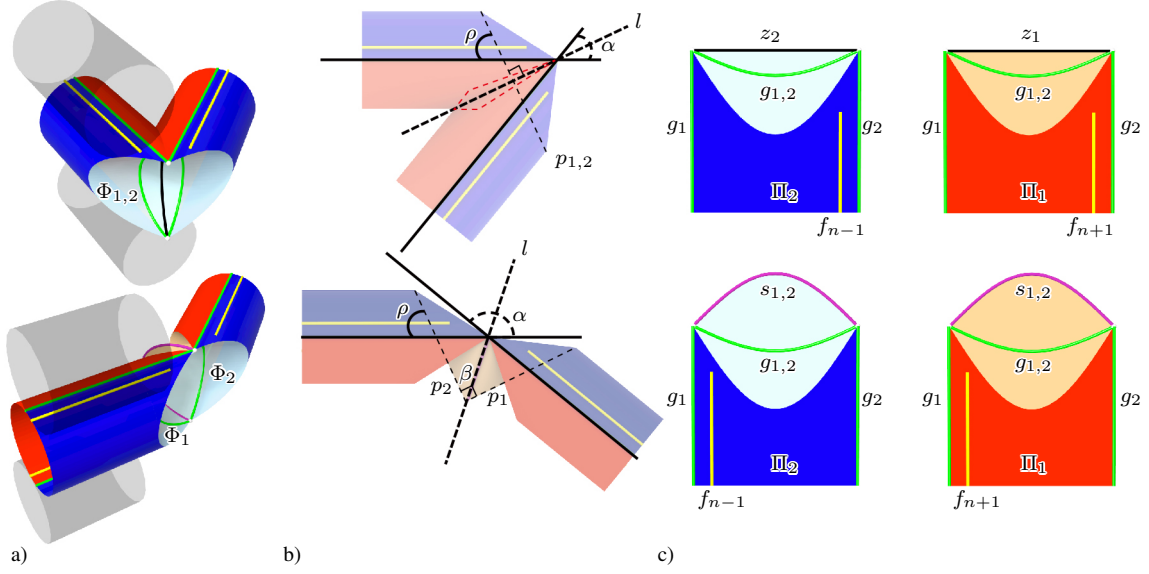


Figure 3: (a) Perspective view of the vertical capping joints for the angles 50.791° (top row) and 140.791° (bottom row) constructed with the mirror-reflection geometry. In the top view (b) the geometric parameters α , β , and ρ can be seen, which characterize the joint configurations. (c) Developed patterns of both joints. The two TPU-laminated textile sheets Π_1 and Π_2 are welded along curves g_1 and g_2 , while $g_{1,2}$ denotes the seam line used to close the air pouch section. In the 140.791° joint, the curve $s_{1,2}$ represents the seam line connecting adjacent air pouches. In the 50.791° joint, neighbouring air pouches are connected through zippers z_1 and z_2 . Curves f_{n+1} and f_{n-1} denote the fusion lines connecting each tube to the subsequent layer ($n+1$) and the preceding layer ($n-1$), respectively.

2.2. Final strategy

To simplify production and to increase its efficiency, we adopted the hinges between neighbouring pouches of the same row in a way that in the inflated deployed state they are all vertically and do not longer follow the underlying T-hedral surface. From a theoretical point of view this change in the geometry destroys the rigid foldability of the structure, but preserves the deflated flat state and the inflated deployed state. Hence, theoretically the structure should already be rigid without closing it to a ring, which is clearly not the case in practice due to arising deformations caused by self-weight.

In detail, the construction of the capping is done as follows: We first determined the joint angle α from the pavilion design, resulting in two kinds of joints whose angles are 50.791° and 140.791°.

Considering the inflated configuration of the 50.791° joint, the connection region between the two air pouches was designed to be on a commonly shared cylindrical surface $\Phi_{1,2}$ to enhance structural stiffness (cf. Fig. 3a). The contour generator $p_{1,2}$ of $\Phi_{1,2}$ regarding the top view (cf. Fig. 3b) is perpendicular to the angle bisector l of the angle α . The corresponding angle parameter ρ can therefore be derived through trigonometric relations and the mirror-reflection principle as: $\rho = 90^\circ - \alpha/2$. The center line of the cylindrical joint surface (black curve in Fig. 3a) defines the designed seam line of the joint. As shown in the developed pattern, adjacent air pouches are connected with zippers z_1 and z_2 at the joint (cf. Fig. 3c). It should be noted that this construction method is not geometrically perfect for this joint angle. The red dashed region in Fig. 3b indicates a small penetration generated in the 3D model of the adjacent air pouches. However, because the membrane material is compliant, these regions deform and locally compress against each other in the physical prototype, thereby accommodating geometric inconsistencies without altering the overall symmetry of the joint configuration. Therefore, this geometric imperfection was considered acceptable in the present design.

For the 140.791° joint configuration, the joint surfaces Φ_1 and Φ_2 between two adjacent air pouches

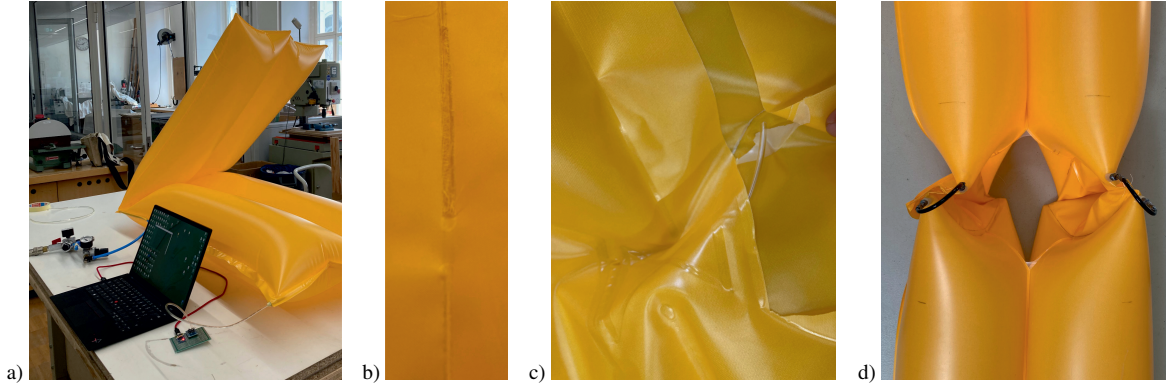


Figure 4: (a) Setup of the bursting test: Beside an inflation valve we inserted a digital pressure sensor over a separate channel into the pouch, which transmitted the data to the laptop. (b) The material ripped up at (b) the point where the welding line between two pouches of adjacent rows was interrupted; (c) the corner where the air channel crosses the eye-shape to the neighbouring pouch of the same row. (d) The fusion welds overshoot the crease curves and therefore they widen up during the inflation. Exactly at these points the material ripped off in the later done bursting test.

cannot form a common cylindrical surface. To maintain the developability of each pouch, Φ_i of each air pouch is extended. The angle between the two extended surfaces of one joint is defined as β . Now the angle parameter can be correspondingly derived from the trigonometric relations as: $\rho = 180^\circ - \alpha/2 - \beta/2$. To improve fabrication efficiency, β was set to 90° . Under this condition, the resulting patterns ensure that the geometry of $g_{1,2}$ remains identical for both joint configurations, as in the 50.791° case.

In comparison to the initial strategy (cf. Section 2.1.) the presented one has the advantage that no crossing seam lines occur and that all curved weld lines are identical, thus only one welding tool has to be bent. The disadvantage is that one segment of the T-Umbrella cannot be constructed just by welding two large sheets of 2-sided TPU-laminated textile. Each pouch has to be produced separately and connected to the neighbouring one of the adjacent row by additional straight welds called “fusion lines”, which run along the generators of the cylindrical tubes between the crease curves (cf. Fig. 3c). As a consequence the resulting T-Umbrella will not be water-tight any-more as there arise gaps at the corners of the cantilevering part, which cause the light pattern on the floor of Fig. 6b.

By using the fusion lines, the distance between neighbouring pouches of adjacent rows drops from the seam width (which has to have a minimum of 2 mm for production reasons) to zero. This reduction of the backlash between cylindrical air pouches increases the structural performance in trade-off for the tensile strength in direction of the rulings, as the material can rip up much easier along the fusion lines. In order to mitigate this problem we used a seam width of 6 mm along these fusion lines, which is doubled the width of all other welds.

Remark 1 *Note that one can glue extra flaps to the ends of the fusion line taking away tensile forces from the weld. We decided not to make use of this method but to handle the structure very gently instead during the deployment process.* $\diamond$

3. Learnings from physical models

In this section we describe our learnings gained from the physical models produced during the development of the T-Umbrella, where we distinguish between test patches, the 1:2 learning structure and the first installation of the large-scale model without stabilizing and seating structure.

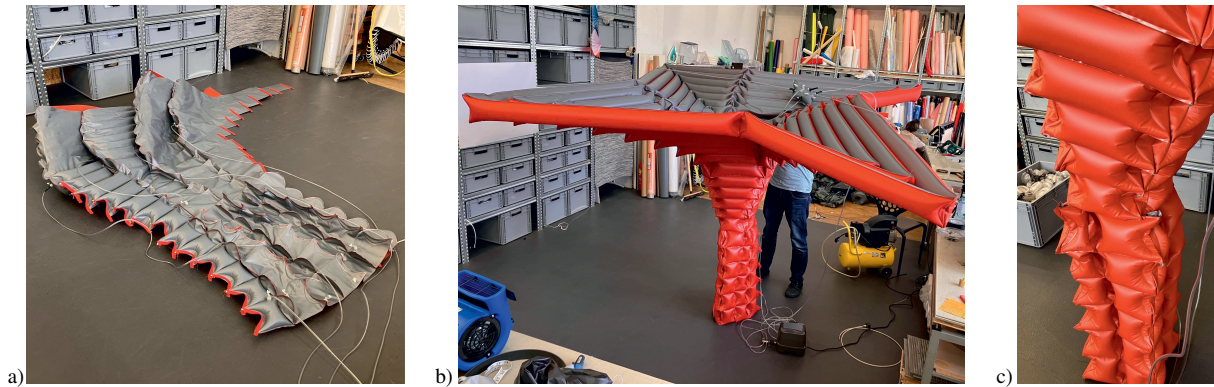


Figure 5: 1:2 learning structure in the deflated state (a) and in the inflated deployed state (b) with a detail of its structural weak point at the trunk (c).

3.1. Test patches

During the development of the T-Umbrella we produced five test patches (see Fig. 4), which consist of several cylindrical pouches (with diameters in 1:1 scale), for the following purposes:

1. Testing the practicability of the cutting pattern; especially regarding the already mentioned crossing of seam lines. We also tested if the fusion welds of the final strategy (cf. Section 2.2.) can be done up to the precomputed crease curves, which will round out in the physical models (see Fig. 4d). From them we learned that a safety distance of 6 cm should be taken into account.
2. Testing strategies for propagating the air flow to neighbouring pouches during inflation/deflation. The inflation tests revealed that the air channels get blocked as the two layers of the 2-sided TPU-laminated textile easily stick together (which is even worse for the deflation process) and each channel has to be reopened by hand, which is not practicable for the final structure. This problem can be resolved by glueing tubes with an outer diameter 7 mm and a wall thickness of 1 mm into these channels (see Fig. 4c) which is a time-consuming task. Moreover, the final strategy (cf. Section 2.2.) does not allow to include air channels between neighbouring pouches of adjacent rows without punching the material (on the fusion line).
3. Bursting tests regarding the impact of the cutting pattern, weld width and placing of air channels on the resistance of the pouch against internal pressure. The bursting tests revealed that the air channels weakened the structure, as exactly at the corresponding welding lines the material started to rip up (see Fig. 4bc). This problem can be faced by relocating these channels closer to the tips of the “horns” of the pouches (or even to connect them over the tips), because in these areas the forces decrease according to the Barlow’s formula. In this context it should be noted that all our bursting tests could verify the data of the producers concerning the strength of the TPU-laminated material.

3.2. Learning structure in the scale 1:2

We have used the strategy of Section 2.2. to realize the geometry of the T-Umbrella presented in [9]. Due to a small inattention in the layout of the fusion pattern these welds were not shortened correctly, thus they started to rip up during the inflation (similar to Fig. 4d). This caused several leaks in the cantilevering part of the structure, as unfortunately we also used the strategy to inflate neighbouring tubes of adjacent rows by punching the material along the fusion lines. Therefore we were not able to inflate the prototype with the intended pressure; but nevertheless the cantilevering part was already stable (see Fig. 5ab). Note that a diaphragm pump was used to inflate a central pillow, which distributed the air to the different sheets.

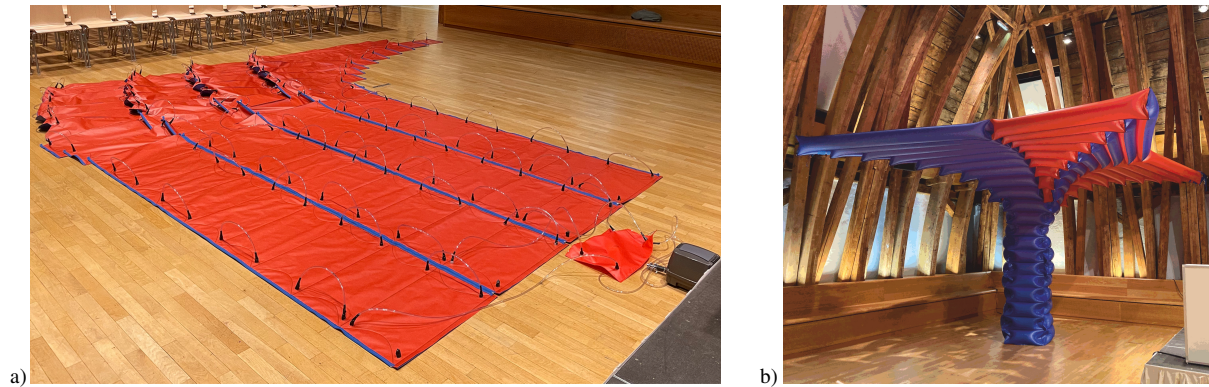


Figure 6: (a) Setup for the inflation of the large-scale model at the Symposium on Geometry and Computational Design (GCD) 2025, TU Wien. In the inflated deployed state (b) the three corners of the T-Umbrella were tied to the wooden cupola to prevent it from tilting over.

The prototype also revealed a structural weak point of the trunk where the geometry was changing due to the crossing of fold lines (see Fig. 5c). To counter this problem, we replaced the crease crossing by a bi-furcation in the final trunk design and straightened the trunk, which also resulted in an increase of its diameter. Note that the redesigned trunk can be produced by the original air pouch technique proposed in [8], which yields a water-tight construction without fusion lines.

3.3. First installation of the large-scale model

In order to minimize potential sources of error in the final structure, we decided not to use any air channels crossing the eye-shapes (see Fig. 4c) or to perforate the material along the fusion lines as done in the 1:2 prototype. Instead we connected the pouches by external tubes (with a diameter of 7 mm and a wall thickness of 1 mm) over valves without non-return function, which are welded into the “horns” (similar to Fig. 4d) where reduced forces arise as already mentioned above. We only used non-return valves at the bottom of the trunk, where each of the four sheets was inflated using a similar set-up as for the blow-up of the 1:2 learning structure (see Fig. 6a). In this case the central pillow had the same diameter of 20 cm as the pouches and we attached a pressure relief valve to it with a nominal pressure of about 0.4 bar (which is half of the air pressure causing a bursting of the pouches) for safety reasons.

The inflation process showed that the used diaphragm pump (power 60 W, max. pressure 0.35 bar, airflow rate 4800 l/h) was not strong enough to reach this upper bound of the internal pressure, thus we replace it by a more powerful one (power 200 W, max. pressure 0.45 bar, airflow rate 12000 l/h) in future installations. The first installation confirmed our expectations, that the most critical phase is the raising of the structure from the horizontal position into the vertical one, in which it can be closed up by zippers to a ring. Nevertheless, this closing stiffens the T-Umbrella, we experienced that the redesigned trunk is still needing an additional structure for stabilization (cf. Fig. 6b), which is discussed next.

4. Stabilizing the structure

Because the structure is very lightweight, its stability against overturning forces—such as wind or people leaning on it—must be ensured through additional weight and a sufficiently large ground contact area. For this reason, the initial design incorporated a seating bench positioned around the umbrella’s central trunk, intended to be filled with water or sand. However, this concept proved to be difficult to implement for several reasons. Establishing a rigid connection between the trunk and the bench was technically challenging, particularly since the bench needed to remain detachable, requiring releasable connections. Solutions such as Velcro or zippers did not provide the necessary stiffness. The trunk also turned out to be slightly curved rather than perfectly straight, caused by buckling under self-weight, as can be seen

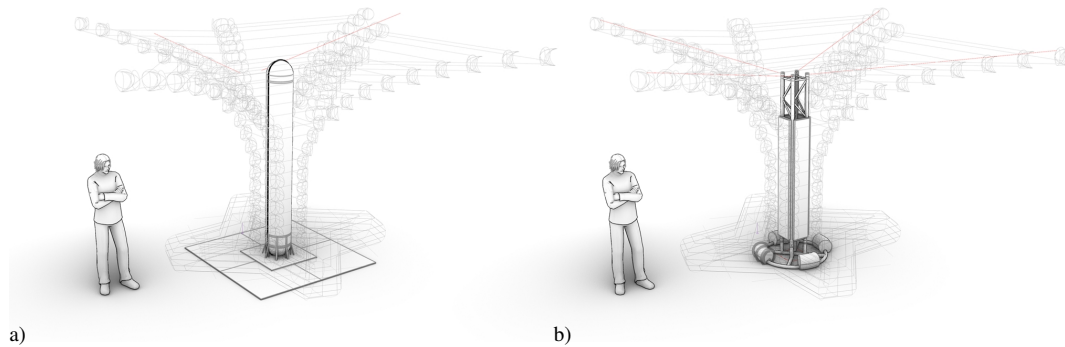


Figure 7: Sketch of the potential stabilization solutions with emergency suspension (red): inflatable tube (a) and rigid frame (b).

in Fig. 6b. Together, these issues made the trunk overly flexible, leading to excessive deformation in the cantilevered portion of the umbrella. Finally, relying solely on the seating bench for stabilization appeared unreliable, especially in public spaces where vandalism could occur.

These insights, derived from the small-scale model and the development of the GCD demonstration, prompted a revision of the stabilization approach. Instead of depending exclusively on the trunk's pouches, an additional structural element was introduced. Additionally, emergency suspension was made possible through this internal structure. Changing the trunk's cross-section to a square shape created suitable internal hollow space for an internal reinforcement structure. As illustrated in Fig. 7, two concepts were investigated in detail: an inflatable tube and a rigid truss, both anchored to a rigid plate rather than to the relatively flexible tubes of the seating bench.

4.1. Internal inflatable tube

The inflatable tube option was favored due to its low weight, which makes it easy to transport, and because it can be deployed using the same equipment required for the umbrella itself. Positioned inside of the umbrella, it stabilizes the structure through direct contact with the trunk's pouches. Its connection to a wooden base plate is achieved by a series of straps attached both to the plate and the internal tube. These straps can be individually adjusted using friction buckles, allowing fine control over the vertical alignment of the trunk. The straps draw the tube's outer shell toward the base plate, thereby absorbing the tensile forces generated by the tube's internal pressure. This prestressing effect creates a bending-stiff connection between the plate and the internal tube. Calculations indicated that, to resist moderate wind loads, the internal pressure of the tube would need to reach approximately 1.2 bar. Achieving this level of pressure would require a higher-grade material than that used for the umbrella, as well as an additional compressor alongside the existing air pump. Consequently, the inflatable tube solution is best suited for indoor applications, where high wind loads are not a concern.

4.2. Internal truss

For applications with higher load-bearing requirements, a variant incorporating an internal aluminum truss was explored. Such trusses are widely used in stage construction, are readily available, and offer a favorable combination of low weight and high stiffness. Modular systems exist in which individual components can be connected with click-fit joints. A standard truss element has cross-sectional dimensions of 29 cm × 29 cm and a length of 150 cm. The outer dimensions of the truss cross-section are slightly undersized relative to the internal void of the umbrella's trunk. This size difference is compensated by inserting 6 cm-thick XPS foam boards between the structure and the truss. Upon inflation, the membrane presses uniformly against the truss, ensuring a tight and stable fit. If additional

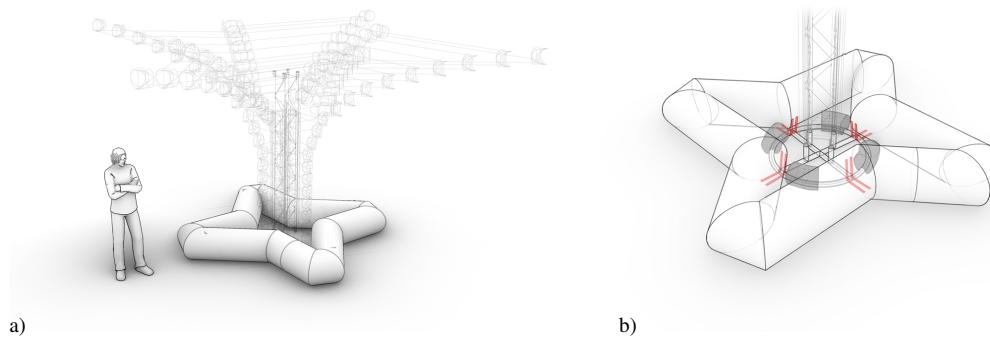


Figure 8: Sketch of the seating structure (a) and its connection to the foundation ring in red as well as the optional additional sandbags in grey (b).

stabilization is required to withstand higher wind loads, a second truss element of 100 cm length can be attached to the primary truss. The upper end of this extension is 50 cm below the highest point of the umbrella, allowing the cantilevered corners of the canopy to be tied to the central truss using ropes. This setup reduces deformation under external loading, as illustrated in Fig. 7. The ground interface is realized with a ring with a diameter of 100 cm and a height of 20 cm, which is included in the manufacturer's modular system. This ring features click-fit connectors designed specifically for the aluminum truss, allowing quick and secure attachment. When needed, the ring can be further stabilized with small, standard sandbags placed between it and the seating structure. In addition, it helps keep the seating arrangement in position, as shown in Fig. 8. The internal rigid truss also facilitates the erection process. As noted earlier, a critical stage during initial inflation was lifting the structure to close the zipper. Since the truss must be assembled and positioned prior to inflation, it can serve as a temporary support framework during this step. The rigid column provides guidance and stability while the structure is being raised, significantly simplifying this operation.

5. Seating structure

As the aim of the project was also to provide a certain quality of stay during the exhibition, the seating was always a crucial part of the design. As explained above, the horizontal forces applied to the structure would endanger the overall stability of the structure, so the surrounding bench was developed in a way to allow for a nice seating quality under the cantilever while simultaneously avoiding that seated persons would use the trunk as a backrest. Therefore, the seating sides were oriented radially from the centre column. The seating forms a tweaked star shape materialised with one single tube with a height of 47 cm. The height is not only given by design aspects, but also by the material's width, which allows for the almost offcut-free fabrication of tubes with 47 cm diameter. Fabrication-driven angle reduction along the fold lines leads to a truncated star shape to reduce the stresses along the welded fold lines. The seating tube is a separate element with one single zipper seam line, so it can be installed after the T-Umbrella is inflated by wrapping it around the column.

6. Conclusion

In this paper, we presented the process, from mock-up to a successful demonstrator for the T-Umbrella. Together with the preliminary work [9], the entire process, from surface interpretation of a complex semi-discrete T-hedra configuration, its realizations with inflatable pouches, the adaptation of the cut patterns, as well as an advanced fabrication method, to an ensuing prototype, can be seen as a guide for other researchers working in this field. Describing the specific problems and their solutions, especially the adaptation of the cut patterns and their fabrication techniques, as described in Section 2., should be highlighted here. As the design and fabrication of deployable mechanisms from zero-thickness surfaces

cause different difficulties on different levels, the authors believe that the documentation and explanation of this specific approach open up new strategies for many other disciplines.

After the IASS 2026, the T-Umbrella will be reused as a fair/exhibition stand at events for science communication and presentation, especially related to the research project SFB F77 of the Austrian Science Fund FWF, which is funding this pavilion.

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