SOFTENING THE HABITATS
SUSTAINABLE INNOVATION IN MINIMAL MASS STRUCTURES AND LIGHTWEIGHT ARCHITECTURES

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TemporActive Pavilion: first loop of design and prototyping of an ultra-lightweight temporary architecture

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Abstract

The paper presents the project development of an ultra-lightweight temporary structure consisting of bending active GFRP arches, a restraining system made of stainless steel cables, and a translucent membrane envelope, with particular focus on the prototyping phase leading to the first construction of the pavilion. A multi-disciplinary team has collaborated to the realization of the first full-scale prototype, built with the aim of deepening a wide range of aspects related both to the optimization of the innovative mix of structural components and to the understanding of the installation constraints, typical of temporary architecture. The paper concludes by showing the results derived from the study and the lesson learned from the first prototype and foreshadowing further studies of the interface between structure and coating, also in relation to the different cycles of use and life-span of the pavilion.

Keywords: temporary architecture, ultra-lightweight structure, bending-active, hybrid structure, membrane, translucent envelope, design, simulations, structural analysis, optimization, prototyping, performance, construction, assembly

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1. Introduction

Temporary structures are increasingly present in urban areas: built for temporary events or ephemeral installations that last from a few days to a few months, they are meant to be disassembled and in some cases remounted elsewhere. When designing temporary structures, which have to be erected and dismantled regularly, costs, weight and the size of the prefabricated components have to be limited (Forster, 2004). Reducing the weight of the building materials seems a good prospect for temporary applications from an environmental point of view, in terms of limiting the resources used for the transportation, assembly and usage phase of the structure. Furthermore, designing demountable solutions optimized in weight allow the structure to occupy a limited volume when not in use.

Ultra-lightweight structures, such as hybrid bending-active structures (Slabbinck *et al*., 2017), represent an efficient response to these needs because both the high performance and the adaptability of their components make these structures suitable for ephemeral and temporary uses (Lienhard *et al*., 2013). The ongoing research conducted by the authors on ultra-lightweight temporary structures deals with specific requirements (e.g. transportability, easy assembly and disassembly, reuse) that are verified in an experimental application. The present paper describes the project development of an ultra-lightweight temporary structure called TemporActive, with particular focus on the prototyping phase leading to the construction of the first prototype. In particular, the first loop of design of the project investigates, on the one hand, the structural efficiency of the proposed ultra-lightweight system and on the other want to verify the effectiveness of the simplified installation process of the active bending arches. The construction of a full-scale preliminary prototype has been an integral part of the iterative design process that aimed at optimizing the erection process and of detailing the first construction of the pavilion in a public space in front of the Politecnico di Milano. Then the second loop of design will be focused on studying the envelope performance of the pavilion for providing a good level of internal comfort regardless of its thin and transparent building skin.

The challenging goal of ultra-lightweight structures is to find the right equilibrium between structural efficiency and a minor redundancy that makes the system resilient to different scenarios and modes of use of the structure over time. The weight reduction of structural components aimed at facilitating transportation and (dis)assembly, which at the same time had to strike a balance with the minimum requirements of temporary structures and with the requirements that a structure built in a public space must fulfil (e.g. above ground foundations, safety, and accessibility). The use of composite materials for the loadbearing structure aof the arches and the H-section beams of the platform allows to considerably reduce the weight of the whole structure. This affected the design of details, by combining the requirements of the bending- active structure and the interfaces between different materials.

2. Project presentation

TemporActive is an ultra-lightweight temporary pavilion that experiments the combination of a bending active structure and a translucent envelope with the aim of facilitating the transportability and accelerating the assembly and disassembly processes, even by non-specialized installers and therefore to promote multiple uses of the structure after the first use. The name TemporActive refers not only to the juxtaposition of the terms "temporary" and "active bending", but also to a wider objective of the project of creating a temporary but, at the same time, active and dynamic space for users, able to change according to the functions and activities that are hosted inside.

The pavilion is a hybrid structural system that combines bending-active fibre-reinforced arches, a restraining system made of stainless steel cables, and covered by a form-active translucent membrane. It consists of 2.00x7.00 m modules, reaching a maximum of 3.50, made of double-wing shape restrained arches. The self-supporting module is designed to be structurally efficient and extremely lightweight, weighing only 50 kg. The modularity of the coupled arches allows the realization of different configurations (e.g. single module, tunnel, S-shape curve, flower shape, etc.) and makes the structure capable of hosting different functions. As first use, the structure in a tunnel-like shape will host in June 2019 the Entrance Pavilion of the TensiNet Symposium 2019 "Softening the Habitats" during one week of events connected to the international conference and the related exhibition IN.TENSION. After the disassembly, a second use of the structure it is planned since the structure will be rebuilt inside the PoliMi Campus as leisure time facility for students. The multiple usages and possible locations of the projects - that are often unknown during the design stage - determine design choices to meet requirements compatible with different functionalities. Given the temporariness of the structure, the technological choices and details have been designed and optimized to facilitate the (dis)assembly process and transportability. For this purpose, the detailed design phase has been made in close collaboration with manufacturers and suppliers to find the most suitable solutions to meet the project requirements.

Figure 1. Different usages of TemporActive

2. Structural behaviour

The shape of the structure is determined by a form-finding numerical model based on both static and architectural aspects. The polycentric arch geometry of the project, when compared with a semi-circumference of the same diameter, allows a considerable optimization of the indoor space. To obtain this form, instead of using pre-formed rigid elements, bending active arches are used, by bending linear elements on site and restrained them with cables. Bending active structures are structural systems which are obtained by elastically deforming an initially straight set of load-bearing elements (Lienhard and Knippers, 2014). The use of straight elements simplifies the assembly process since the actively-bent elements can be pre-assembled on the ground and erected afterwards (Liuti *et al*., 2018). A cable restraining system is located in the inner part of the arch with a threefold function of obtaining the desired geometry, limiting and controlling the deflection of the bent elements and making the structure more resistant to external loads. The restraining system enables the total stiffness of the structure to increase despite the reduced size of the structural profile that can, therefore, be kept smaller and optimized for the bending process (Alpermann *et al*., 2012).

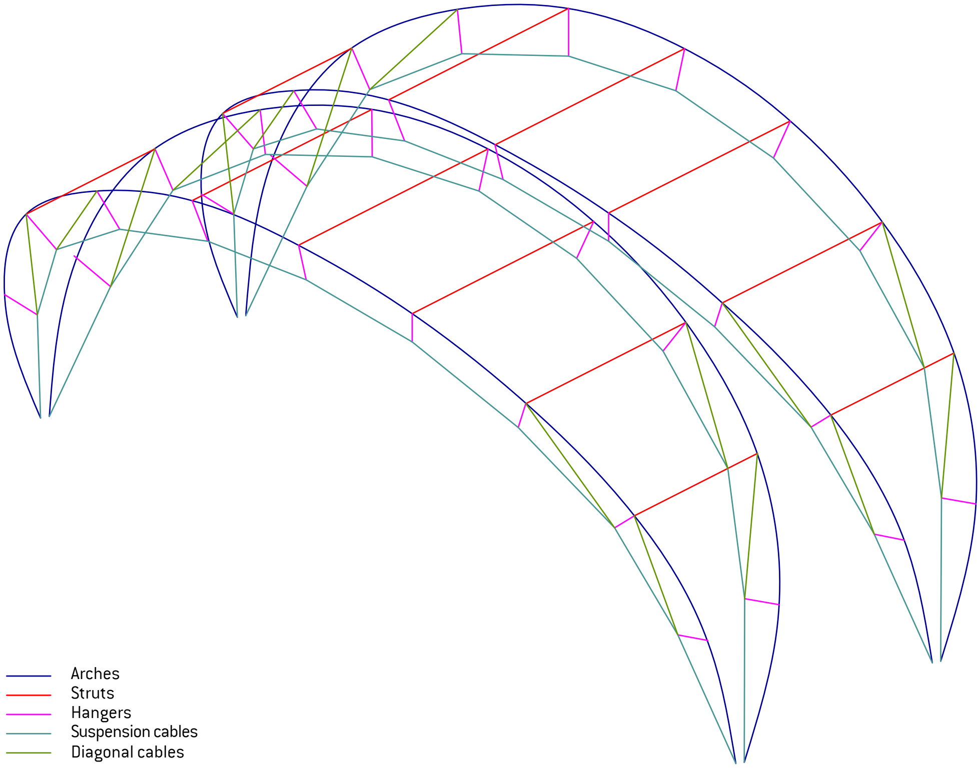

Figure 2. Structural elements

To bend the structural profiles in the polycentric arch geometry the right material needed to be found, able to be easily bent but at the same time to withstand the design loads. Glass fiber-reinforced polymers (i.e. GFRP) meets the criteria required in terms of elasticity and strength (Kotelnikova-Weiler *et al*., 2013). Considering the safety factor of the material, it was found that the GFRP tube could be bent in the lateral part of the polycentric arch (minimum radius of curvature R = 220 cm) only if each tube had a cross-section diameter of less than 2 cm. Due to the limited dimension of the profile, three tubes are combined to form a triangular-shape profile. Each arch consists therefore of a bundle of tubes made up of three GFRP tubes 26x19 mm, 11.50 m long, with a span of 7 m. The combination of multiple smaller diameter tubes allows the arch to be bent according to the required geometry but, at the same time, to resist design loads without buckling.

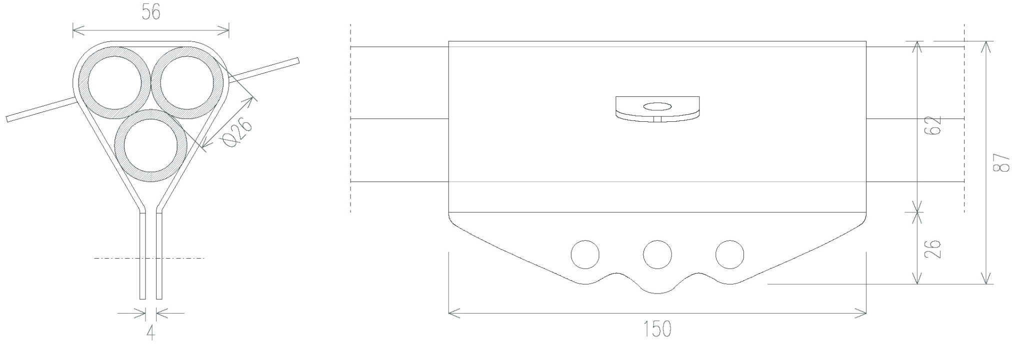

Figure 3. Structural profile composed of a bundle of three GFRP tubes 26x19 mm and its connector

The form-finding and structural behaviour of the structure have been analysed with TLLoad, developed by Mike Barnes / formTL, using the dynamic relaxation method. The structure composed of i) GFRP arches made of bundles of three Ø 26x19 mm actively-bent tubes, ii) stainless steel cable restraining system in the inner part of the arches, iii) GFRP struts placed between the two-wings arches to stiffen and stabilize the structure, and iv) the transparent envelope made of 200 µm ETFE foil results suitable and resistant to the applied loads in accordance with EN13782 - Temporary structures (i.e. snow load s= 0.2 kN/m, wind load q= 0.5 kN/m²).

3. Full-scale preliminary prototype

The first prototype was built with the aim of i) demonstrating proof of concept for this design approach; ii) verifying the installation process, i.e. easy bending of the GFRP tubes; iii) better understanding the structural performance of the system and comparing its behavior to the form-found geometry; and vi) to check the technological details (e. g. connections, membrane behavior, etc.).

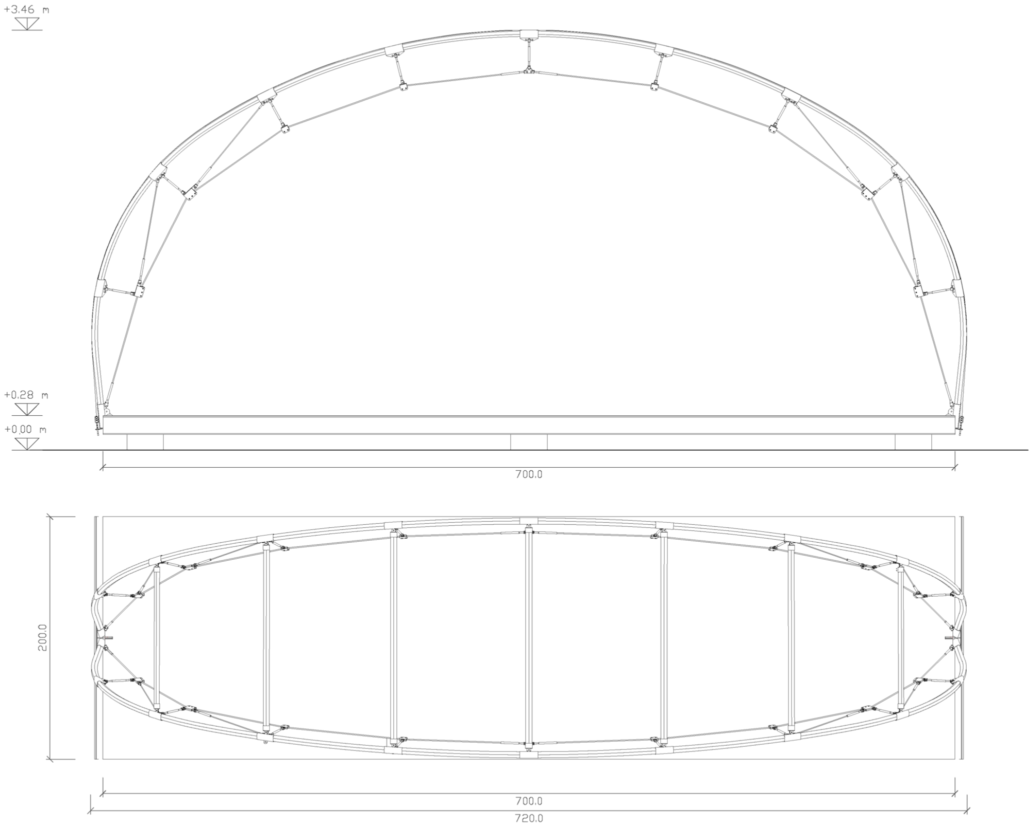

Figure 4. Dimensions of one module of TemporActive

3.1. Specifications

The full-scale preliminary prototype made of two modules of TemporActive covered a footprint area of 7 x 4 m and was 3.20 m high. Each of the four arches was built up from a bundle of three GFRP tubes connected together with 3 mm stainless steel connectors folded in a triangular shape. The restraining system consisted of: i) Ø8mm stainless steel cables parallel to the arches; ii) Ø6mm stainless steel diagonals cables in the lateral part of the polycentric arch, which do not have high tension force but that contribute to increasing the overall stiffness; and iii) turnbuckles 250 mm long to connect the cable clamp with the arch connector, by means of both ends double fork. The length of the cables and the tension required was derived by the form-found geometry. Five struts, made of coupled GFRP tubes 26x19 mm, were placed in the topper part of the arches to spread the arches out and to balance the inner forces resulting from the foil that introduced a lateral force into the end arches and wanted to press the arches together. As a consequence to the large deformations of bending-active structures during the erection process and the consequent transition from straight to curved elements, the connection details must be carefully designed to allow movement during the erection/bending phase of the structure and then to be blocked once the structure has reached the final geometry. The arches were connected to the ground by means of two-piece stainless steel connectors. A hinge between the two parts of the connector allowed the arch to rotate during the assembly phase and was locked once the arch was in position. Folded stainless steel brackets served as intermediate connectors, allowing the sliding of the lower tubes of the bundles during the bending phase. The connectors were tightened once the arch was erected, before fixing the restraining system.

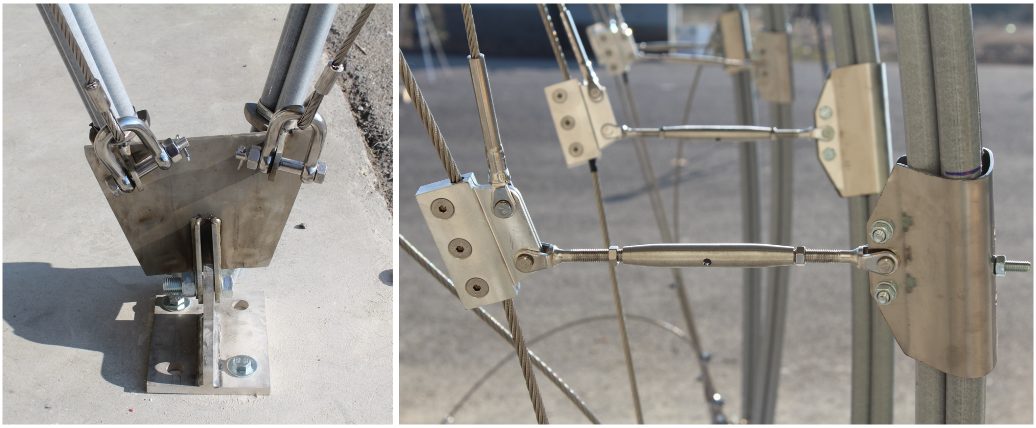

Figure 5. Base and intermediate connectors details

The envelope was realized with a clear ETFE foil, 200 µm thickness. Given the reduced size of the structural profile (52 mm total width of the arch vs 60 mm width of the standard double keder rail profile), a research was done to find a suitable connection system for the membrane in terms of size and flexibility. Initially, it was thought to use plastic single rail keder profiles since there was not too high force. However, this option has been abandoned in favor of aluminium profiles because the PVC profile deformed too much. To test two different options in the prototype, an aluminium single keder rail was installed on one side and an aluminium single keder rail coupled with an aluminum strip on the other. The second solution resulted more efficient because it prevented the keder rail buckling when the cloth was under tension. The one-piece foil was connected to the first and last arches, without any intermediate fixation, by means of an aluminum single keder rail bolted to the stainless steel connectors every about one meter. The frontal keder rails must be installed after the erection of the structure because otherwise, they behave as active bending elements as well.

3.2. Assembly process

The assembly procedure was first studied with the help of scaled models but it was mainly verified during the first full-scale prototype installation. The prototype construction required the intervention of at least three people who worked full-time for two days. In some phases, e.g. during the membrane erection, the intervention of a greater number of people was necessary. No high forces are necessary to bend the arches and to tension the restraining system, therefore no strong machinery were required for the installation.

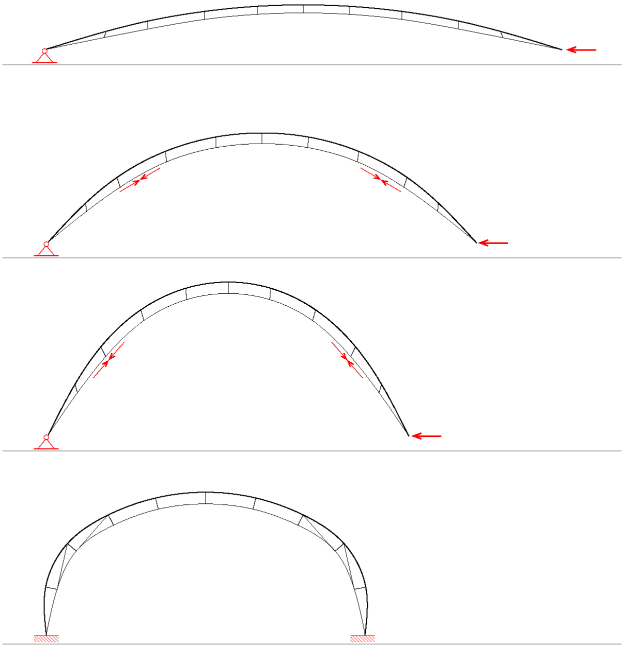

Fig. 6. Bending sequence during the erection of the arches: from the ground to the catenary shape until reaching the final geometry.

The arches were pre-assembled on the ground (i.e. by inserting both base and intermediate connectors, and connecting the restraining system and the struts) e then bent with the help of a manual wire rope hoist. Once the first phase of the arches erection was finalized, reaching the catenary/semicircle shape, the restraining system was fixed to the lower part of the arch and cables were tensioned in order to obtain the final geometry. After completing the erection procedure, it was verified that the geometry obtained corresponded with the project form-found geometry. During the prototype construction, this phase took longer than expected because the geometry has been affected by the asymmetrical assembly mode of the structure. Once the correct geometry had been obtained, the connectors were fixed in place following the marking on tubes, the clamps were tightened at the cable markings and the base connector hinges were locked in order to obtain a rigid joint.

Figure 7. Second module erection during arches bending

Afterwards, the one-piece ETFE foil - rolled and placed at the top centre part of the structure - was unrolled and then fixed to the two end arches with the help of ratchet bands and elastic ropes as tensioning devices for the foil. The ETFE foil was tensioned by pushing in two directions: first perpendicular to the arches to fix the keder rail along the arches' development, then parallel to the arches in the lateral part with the help of a threaded bar. The foil did not cooperate much with the arch-struts structure, having mainly a bracing function; however, after the ETFE installation, the structure was found stiffer and less subject to lateral deformations. ETFE foil is more rigid than textile membranes and it seems not allow to accommodate the movements and high deformations of the bending active structure. For this reason, the hypothesis of changing the envelope material for the final construction is being considered or, otherwise, lower compensation should be given to ETFE for best results. or, otherwise, lower compensation should be given to ETFE for best results. Further studies about the integration of foils in bending active structures should be performed in a new mock-up.

Figure 8. ETFE foil installation

Figure 9. Views of the finished full-scale prototype

4. Discussion and optimization

Both the assembly procedure (e.g. tensioning system and adjustments of the restraining system only on one side) and technical details (e.g. base connectors and plates) has affected the behavior of the final geometry of the first prototype. The erection procedure will therefore be optimized, pre-assembling the straight arches with the un-tensioned restraining system on the ground and then only bending the structural profiles and tensioning the inner cables. In addition, optimization of technical details can further simplify the assembly procedure (e.g. shaping the intermediate connectors to allow the rotation of the restraining system during bending, adding tensioning devices in the inner cable to reduce the length of the cable symmetrically from the two parts of the arch simultaneously) and improve the performance of the structure (e.g. increasing the number of struts to give greater rigidity to the structure).

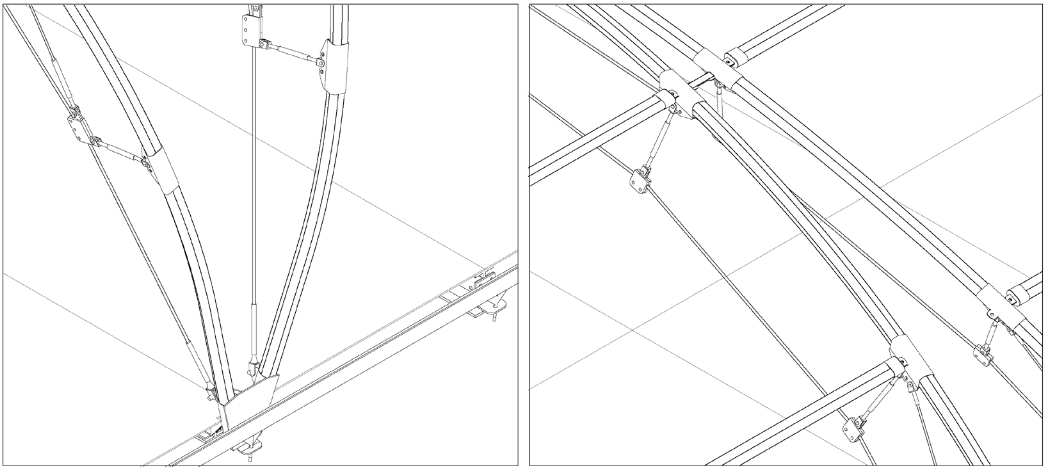

Figure 10. Details after the optimization phase

For the first construction of TemporActive in occasion of the TensiNet Symposium 2019, seven modules will be built, covering a footprint area of around 100 m² in front of the Politecnico di Milano in a public square. The location of the structure in an open public place has influenced the optimization of the tested details and the implementation of the post-prototyping project in two aspects: i) the bending active arches will be connected to a platform made entirely of GFRP H-section beams with adjustable legs and suspended ballast; ii) the installation procedure, having only two days for occupation of the square before the event begins and only one day after the event. This has resulted in scheduling the pre-assembly phase of the straight arches and modules of the platform the week before and then transporting them to the site for assembly. For the pre-assembly and assembly phase, a group of students will be involved. The methods and tools of communication of the pre-assembly and assembly phases to non-specialized people will also be considered in the study.

5. Conclusions and further steps

The construction of the prototype was a fundamental development and verification phase of the TemporActive project before the first construction; however, it is not the arrival point since the research will continue both in the construction phase of the structure and after the event when the pavilion will be reassembled elsewhere for its second use.

The possibility to build an innovative temporary structure is the opportunity to present results of the most recent scientific researches to international researchers, students and citizens, and at the same time to monitoring the structure in order to measure its performance over time. With the first design loop, we verified the behaviour of this hybrid structural system and we had developed the assembly procedure. In the coming months, the research will continue with a second design loop focused on the envelope and in particular on the study of comfort for a transparent envelope by testing and monitoring the performance of different materials and typologies. In parallel, the studies already started on the Life Cycle Assessment (LCA) will be carried out to evaluate the environmental impact of TemporActive. The reflection on the environmental impact of ultra-lightweight temporary structures aims on the one hand to use less metal and materials with a lower embodied energy and on the other to include the time variable in the design process, considering the multiple cycle of use of the structure and not just the single use.

Acknowledgements

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