A removable textile hybrid structural screen for the windows of Castello Sforzesco, Milan: when experimental metrics inform the bespoke “design-to-construction” process in historical contexts

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Abstract

This paper presents the completion of the experimental design-to-installation process of two textile hybrid window screens, aimed at mitigating the comfort conditions and preserving the frescoes of Sala delle Asse at Castello Sforzesco, one of the most important artefacts of cultural heritage in Milan.

Given the historical relevance of the context, the main challenges that the project tackles are: 1) implementing bespoke, low impact, lightweight structural screens as reversible additions to historical buildings; 2) enhancing their performance in terms of visual, lighting and hygrothermal comfort; 3) then creating and validating an interdisciplinary methodology of managing the whole design-to-costruction process, with the aim to assess its replicability in other cultural heritage sites.

The design task, led by Textile Architecture Network, at hand is to produce self-standing vertical screens for the large-scale windows in the room, in order to control the sunlight amount on the frescos, as well as to block air drafts that cause humidity inside the room. The main challenge of the project proved to be the fragility of the direct context, since the screens must be sealed on the borders, but no perforations are allowed on the vaulted edges of the windows. Thus, a textile hybrid structure is proposed as a solution, made of : 1) bending-active and form-active elements, due to its self-standing principle that would not require drilling on the vault; 2) unconventional knitted textile materials, that need to be characterized both in terms of stretching properties and optical performances. Eventually the paper presents the preliminary multidisciplinary research campaign consisting of: 1) *in situ* anemometric tests by Experimental Mobile Laboratory; 1) material tests on optical transmittance carried out by SeedLab; 3) mechanical tensile tests and the updating of the material choices by Textile Architecture

Network, all part of the Architecture, Built Environment and Construction Engineering Department's Labs at Politecnico di Milano, Milan, Italy.

Keywords: lightweight structures, historical context, textile hybrid, interdisciplinary, experimental campaign, mechanical tests, anemometric tests, optical tests, bespoke, design methodology.

Introduction

The study focuses on the improvement of energy efficiency through the creation of a novel ultra-lightweight screen to be applied in a specific historical context, Castello Sforzesco, one of the most important listed historical buildings of Milan, Italy.

This paper aims at projecting this singular case into the broader theme of minimizing the effect of added structures in restoration interventions, as well as giving a framework of collaboration between different fields of expertise when it comes to their design.

In the last two decades lightweight architecture has found applications in diverse contexts ranging from small-scale pavilions to large-scale stadium canopies. Recent advances in composite material production and industrial membrane manufacturing have been a catalyst in making lightweight structures a widespread architectural solution. Their optimized use of material, efficient load distribution and light impact on their surroundings are the main advantages with respect to traditional building systems. Recent relevant lightweight structure applications in historical contexts include the temporary canopy for the annual festival of the Olavinlinna Castle in Finland and the roof covering the biggest courtyard in the Vienna City Hall in Austria, that were both installed for the first time in 2000 (Bögner-Balz, Zanelli, 2007). These two examples show the main potentials of tensile structures when combined with cultural heritage. In the case of the Olavinlinna Castle, the impact on the existing building was minimized and the structure was installed and dismantled recurrently throughout its lifespan. The project for the Vienna City Hall gives an even better example by employing a membrane canopy that is permanent. In that case, the potential of retractability was exploited to provide a flexible solution that can be adapted seasonally (Koch, 2004). Both these notable case studies are recent, however they also prove through their successful application for almost two decades that lightweight and textiles-based structures are highly compatible with historical buildings, which require careful and non-invasive approaches when it comes to contemporary interventions (Rosina et al., 2011; Zanelli, 2015). The experimental work here presented aims at broadening and pushing forward the use of lightweight structures as a mean for a reciprocal benefit of both conservation and management of cultural heritage assets. Coherently with a precautionary principle which favours the employment of short-term reversible techniques for the preservation and historical buildings and their daily care management, this multidisciplinary study shows the first experimental application of an ultra-lightweight and metal-free building system, a bespoke structural window screen, whom novelty deals with the accuracy of the multidiscipliry analysis supporting the materials choices and the structural concept, as well as the few invasive installation procedure.

The delicate context and the design requirements

The castle was initially built by the Duke of Milan, Francesco Sforza, in 1452 and later restored by architect Luca Beltrami in 1893-1903 (Castello Sforzesco, 2018). In the light of the restoration of Sala delle Asse, a room of the castle famous for its vault

covered by Leonardo da Vinci's frescos, the need was the development of novel protective curtains on the two 6 meter high and 3 meter wide windows of the room. The project for the window screens posed a challenge because of the many design requirements to fulfill, some of which being in conflict with each other. These requirements were emphasized by the Castello Sforzesco officials that are in charge of Sala delle Asse's cultural heritage, thus had to be respected to the largest extent.
Firstly, the innovative curtains are required to perform as shading devices that stop harmful UV radiation from reaching the frescos, but also as window screens that stop air currents from going in and passing through the room. The existing window frames were installed in the '50s and thus perform badly in terms of airtightness. However, they cannot be replaced due to being designed by the renowned Italian architectural firm BBPR, which adds to their historical value.
In addition, it was crucial to mantain a visual connection to the surroundings of the castle and the Sempione Park, because the room will be used as part of the museum.


Figure 1: View of Falconiera tower from the outside, where the two affected windows can be seen in the bottom floor.

The Sala delle Asse is located on the first floor of the Falconiera tower on the north-east corner of the castle (Fig. 1), thus one of the windows faces north-east and the other north-west (Fig. 2). The mostly northern orientation of this room means that direct sunlight reaches it only in the summer during early morning and late afternoon hours. If significantly opaque curtains were used, the room would be at risk of getting very little sunlight during winter and autumn, especially in cloudy days. A translucent fabric would need to be used in this case and this is where the idea of knitted textiles emerged, given their ability to provide a visual connection with the outside as well (Kolo, 2018). The two windows are similar in shape and dimension, but given the historical context, they are not identical. The restoration still ongoing in the room have made direct measurements difficult in the first design phase; however, as soon as the restoration ended and the scaffolding was dismantled, the authors would have been able to test the first mock up of the screen (Fig. 3). Due to the short time available without any scaffolding, a flexible solution, easy to handle and to be adjusted on each window, seemed successful compared to other technologies.

One more significant factor was that the new structures for the two window screens are meant to be fixed. The Castello officials reported that the current curtains, which consist of ordinary sliding drapery, are often moved by the museum employees and sometimes used to access the windows and open them. This is highly detrimental to the controlled climatic conditions inside the museum, that are supposed to be kept at a constant humidity level for a proper conservation of the artifacts. In order to tackle the humidity and especially the air draft problem, the new curtain structures would have to be sealed

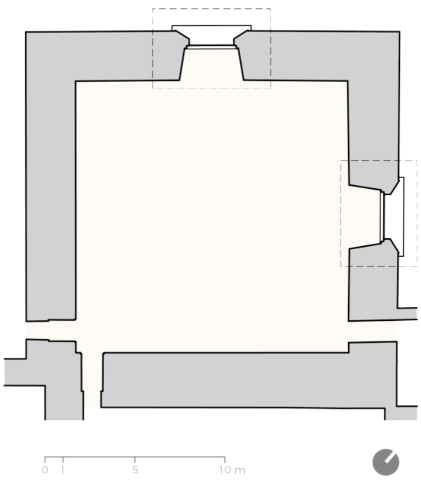


Figure 2: Floor plan of Sala delle Asse, which shows the orientation and location of the windows (Kolo, 2018)

Figure 3: The Sala delle Asse after the restoration works, where the authors alternately obscured one of the two windows to check the light conditions.

in the borders and one of the requisites was to make as few perforations as possible on the walls, especially on the arched part of the vault. However, another conflicting requirement was to have the ability to remove the fabric and wash it for future maintenance. These requirements are where textile hybrid structures started to be consolidated as a solution, due to their potential of providing a self-supporting arch for the vault with the help of bending active elements, as well as reducing the number of perforations on the walls to the minimum amount required for safety, because of their inherent equilibrium properties.

The challenge: integrating a textile hybrid system into a listed building

Hybrid structures have been widely explored in state of the art experimental applications within the field of lightweight architecture, since they were only recently added as a separate structural type as defined based on structural action and load transfer. According to Engel, the main structural types were limited to section-active, vector-active, surface-active and form-active structures (Engel et al., 1997). However, in a later classification by Lienhard (2014), he added bending active and hybrid structures to the main types, by defining the former as *'curved beam and surface structures that base their geometry on the elastic deformation of initially straight or planar elements'* and introducing hybrids as the intentional combination two other complementary structural systems. He refers to structures that use form-active and bending-active principles specifically as textile hybrid structures, which gain their efficiency in force distribution due to reciprocal stress compensation and opposite system deflection, factors that make a hybrid structure more rigid than the components it started with (Lienhard, 2014).

The first notable precedents in terms of textile hybrid structures came as a result of the research of Sean Ahlquist, with the first one being the M1 Textile Hybrid exhibited in 2012, later his StretchPLAY sensorial project, and further the 2013 Toroidal Structure exhibited in the Material Equilibria installation by ICD in Copenhagen, Denmark. The latter was the first time in which a CNC-knitted fabric with structural differentiation was used. This optimised the stretchable fabric for maximum tensile strength and trained it to obtain the desired form (Ahlquist, 2014).

However, the most architectural examples in the category are the hybrid gridshell prototype by Kengo Kuma (Taichi, 2016) and the Hybrid Tower by the Centre for Information Technology and Architecture (CITA) at KADK. These two examples tested the ability of textile hybrids to resist extreme weather conditions. Hybrid Tower especially brought together all the knowledge about hybrid structures by implementing custom-made pockets embedded in the knitted fabric, slender elastic Glass Fiber Reinforced Polymer (GFRP) rods and computational analysis to produce a self-standing structure reaching a height of 9 meters (Thomsen et al., 2016).

The experimental process presented in this paper tries to combine the knowledge gained from the previous expertise in textile hybrid structures to tackle problems surfacing from a multidisciplinary analysis of the site. The differentiation potential of the knit pattern is thought to contribute to the optical and anemometric requirements in terms of the screen's performance and the slender elastic GFRP rods are aimed at providing a low-impact installation rather than a structure withstanding extreme loads. While previous textile hybrid applications are ground-breaking in their structural and customisation achievements, they are usually designed as installations without specific functions. The challenge posed in this paper is to provide a textile hybrid with a very specific purpose, the one of a window screen that is capable of satisfying climate controlling and comfort requirements.

The multidisciplinary approach supporting the early-design stage

The conducted interdisciplinary experimental campaign aimed at optimizing the window screens for visual, lighting and hygrothermal comfort, in addition to evaluating the feasibility of the project and satisfying the imposed design requisites. The full scheme of the interaction between several sectors of different expertise is shown in the diagram of Figure 4, which proposes an integrated feedback process instead of the usual linear one that is commonly applied in conventional architectural interventions. The exchange of information between the various fields starts at an early stage of the design process and continues throughout the later stages by constantly refining the novel building product.

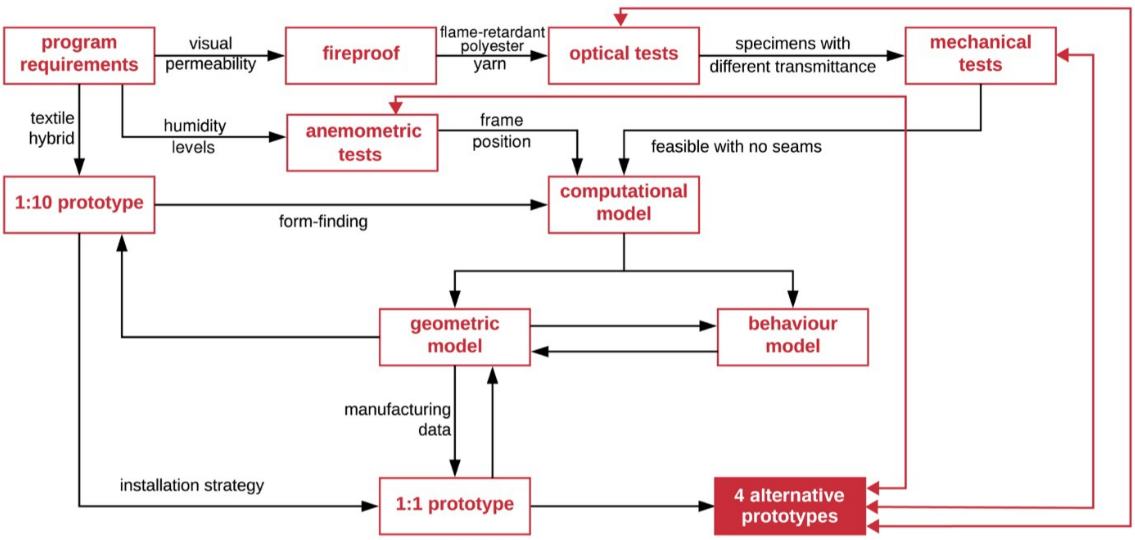


Figure 4: Flow chart of the various competences involved in the project, showing the feedback loop of their interaction; black arrows show exchange that was already applied, while red arrows show future exchange (Kolo, 2018).

The experimental campaign starts by performing preliminary anemometric measures on the current conditions of the room and by parametric modelling the illuminance level based under predefined sets of optical properties of the glazing and of the internal and external surfaces. These analyses gave results on the preferred position and optical properties, in terms of visual and solar transmittance, of the required shading systems. Consequently, a selection of suitable textile materials with not only adequate mechanical properties but also optimal optical qualities was made. The idea was to guarantee adequate levels of illuminance, avoiding disturbing glare and filtering most of the entering direct solar radiation, enhancing user's comfort and preserving Frescoes inside the room.

The chosen materials to be implemented in the project are required to be flame retardant to abide by the national safety regulations, thus the choice of the types of knitted fabrics was limited to the ones using the flame retardant yarn. Among these, the ones with the right visual qualities were chosen, in order to guarantee adequate levels of illuminance, avoid glare and filter direct radiation. The textile materials then went through further optical tests to check their compatibility with the comfort requirements, such as measurements of solar and visual transmittance.

Design choices were updated with these test results and were followed by mechanical studies on the stretching properties of the knitted textiles to define the project's feasibility. These data served as an input to a computational simulation of the structure's behavior, which aided the construction of a real scale mock up to test the bending active principle and the dimensioning of the glassfibre-reinforced elements (Fig. 5). The mock up is also seen as an element of the loop, which gives experimental results on how to change the structure in the following design steps.

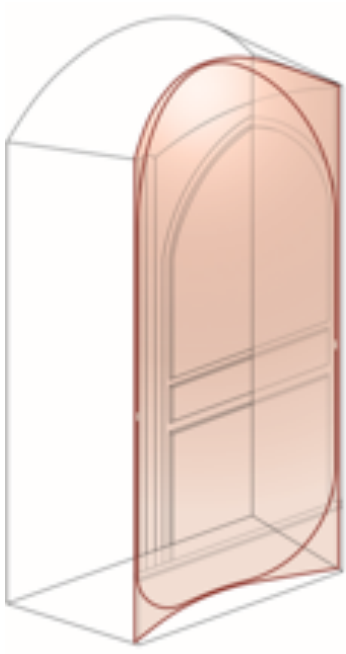


Figure 5: Shape of the bending-active self-standing structure (Kolo, 2018)

The first 1:1.5 scale mock up was very useful to test the bending active principle and the dimensioning of the glassfibre-reinforced elements, while a further 1:1 scale demonstrator gave us later further knowledge and expertise on the behavior of the removable kit of the whole tensile screen, looking for the final optimization loop of detailed design. In refining the workflow, it was concluded that the final step of verification would be to test four alternative prototypes on site with different densities of the textile, in order to conduct final tests in each field of competence about the fulfillment of the comfort and feasibility requirements. These four options consist of low, medium and high-density fabrics that are chosen based on the transmittance range results from the optical tests and simulations, with the addition of a fourth mixed-density fabric that was thought as an experimental solution that is customized specifically for this design task. This final solution will have a denser fabric in the borders to stop air drafts and a finer knit on the inside portion, following the shape of the window, which will let more light in the room, given its northern orientation (Fig. 6).

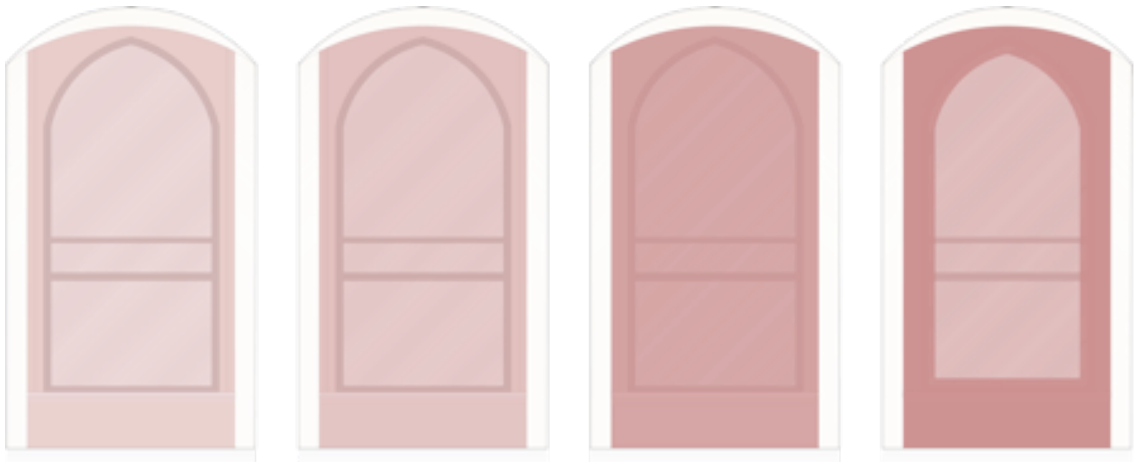


Figure 6: Shape of the bending-active self-standing structure and the 4 alternative prototypes to be tested (reference: TAN group, ABC Dept, Politecnico di Milano).

Modelling and experimental testing campaign

Anemometric measurements

The authors measured the speed of air inside Sala delle Asse and in the corridors connecting the Sala with the rooms nearby (Sala del Gonfalone, Sala 11, Salette Nere), between March and April 2017. The aim of the measurements is to localize and measure the speed of the air fluxes between the rooms and close to the NW-NE windows in Sala delle Asse. As an example, the following table (Table 1) shows the results of two days in December 2016, as well as the events classified by the angle of incidence of the wind on the NW wall, registered in March 2017 (Table 2). The used instrument is an anemometer (hotwire), and the authors took the measurements along a regular square grid, pace about 1 m, covering the entire area of the room, at about 1,20 m from the floor.

N° events	**Date**	**Δ RH% inside**	**Δ hours**	**Direction of wind**	**Frequent wind angle**	**Δ hours Drift**
3	27/12/2016	64,5-28% **37,5%**	9:00-15:00 **6 Hours**	S-SE	316°-345°	2
4	29/12/2016	59-56% **3%**	2:00-12:00 **10 Hours**	N-NW	125°-130°	2

Table 1. Frequences, direction and wind speed, collecting data on 27, 29 December 2016 (Experimental Mobile Laboratory, ABC Dept., Politecnico di Milano)

ANGLES	ANGLES FREQ.	SPEED ≥ 6 m/s
≤15°	5	0
16°<30°	5	0
31°<45°	2	1
46°<60°	3	0
61°<75°	6	0
76°<90°	8	0
91°<105°	17	0
106°<120°	90	0
121°<135°	470	23
136°<150°	15	1
151°<165°	3	1
166°<180°	5	0
181°<195°	1	0
196°<210°	2	0
211°<225°	0	0
226°<240°	0	0
241°<255°	2	0
256°<270°	0	0
271°<285°	3	0
286°<300°	5	1
301°<315°	17	4
316°<330°	57	11
331°<345°	23	3
346°<360°	5	0
TOT. data	**744**	**45**

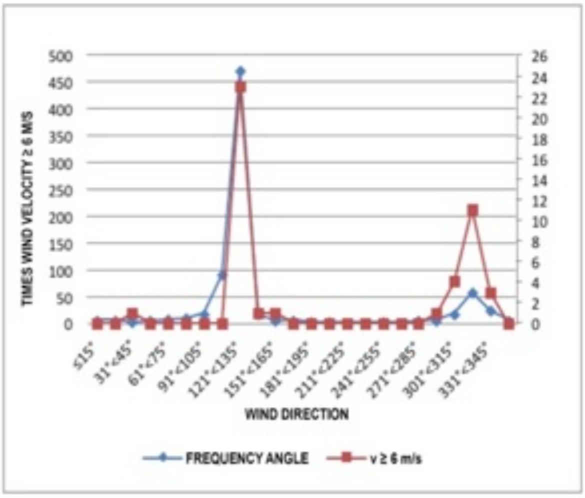


Table 2 . Events classified by angle of incidence of the wind on the NW wall on March 2017 (Experimental Mobile Laboratory, ABC Dept., Politecnico di Milano)

Lighting Modelling and Optical measurements

The main goal of the proposed analysis was double. Firstly, to give a contribution to the exploration of alternative and innovative textile materials; secondary to assess their optical radiative properties. In particular, the research approach was focused on:

- Gaining the maximum availability of daylight, ensuring at the same time its quality, ensuring the smoothness of light distribution inside the spaces;
- Controlling both direct and diffuse solar radiation (on hourly basis) avoiding disturbing glare that can affect users, but also the negative effect of the direct interference of solar radiation with Leonardo’s frescoes surfaces.

The parameters considered significative within the results of the simulations were: the mean illuminance level (lux), measured on both site plan and vertical surfaces adjacent with frescoes; the illuminance levels distribution and evaluated as percentages of occurrence under different ranges (% lower than 100 lux; %between 100 lux and 2000 lux; % greater than 2000 lux). The effectiveness of the shading system was simulated under severe conditions, under the presence of direct solar radiation and for significative sun positions (summer and winter solstices).

The baseline considered for simulations was equivalent to Sala delle Asse, under unshaded conditions, without any shading device materials on transparent surfaces. The light transmission of the glass and the reflectance of the internal surfaces was known or was considered according to scientific literature. The baseline results were used to assess different qualitative and quantitative variables such as: exposure duration and incidence of the direct radiation on internal surfaces, quantity and quality of natural light.

Solar Radiation mapping and daylight distribution - Simulations

The first analysis carried out has been used to map the presence and average extent of direct radiation on the surfaces inside the "Sala delle Asse" during different periods of the year and for different time slots. The images are representative of the cumulative value of direct sunlight during day twentyfirst for each month (Figure 7).

Then a parametric approach has been adopted for modelling the availability of natural light. And the variables that have been considered were:

a) the sky conditions (CIE overcast and sunny clear sky);

b) the visible transmittance (τ_{vis}) of textiles (under 3 macro-categories with different openness factor);

c) the performance of the average system constituted by glazing and indoor fabric shading ($\tau_{vis,tot\ component}$)

This parametric analysis has allowed identifying the threshold of textile optical properties (effectiveness) and is considered as a preliminary benchmark to reduce the selection of the textile samples and whose optical performance was needed to be measured. As a result a range of the optical-radiative properties for the fabrics, maximum and minimum values of τ_{vis} for the fixed shading device were defined as a threshold to filter the radiation and to control the natural light in the environment under different sky conditions (clear with sun and overcast sky).

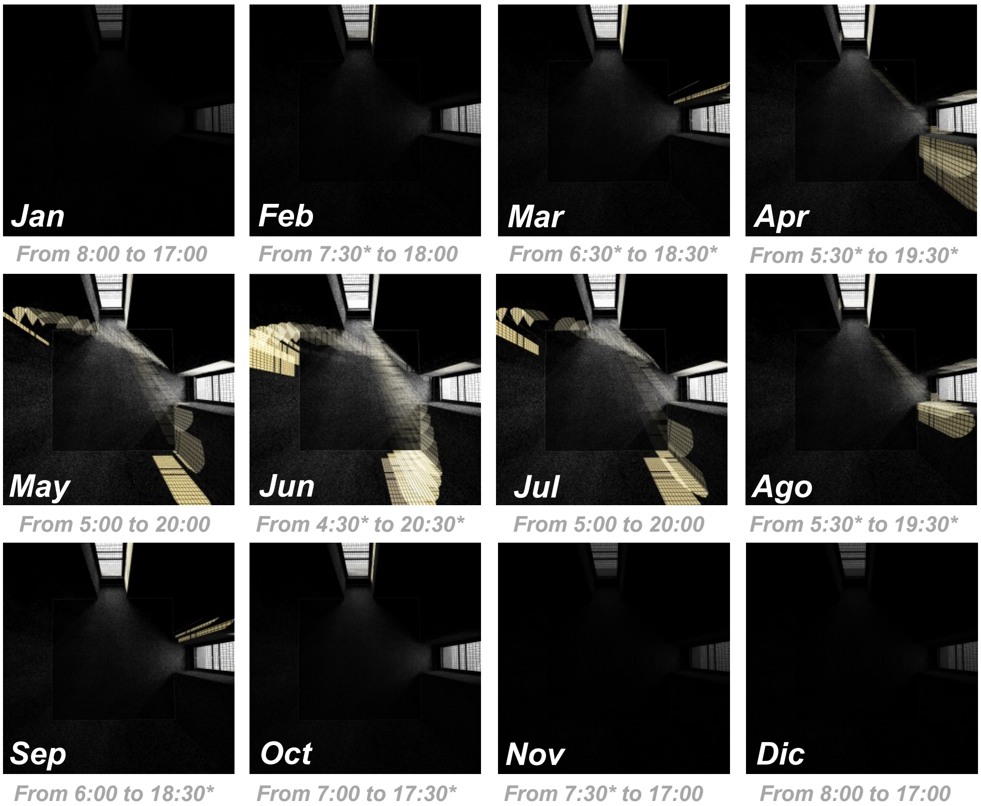


Figure 7: Top view of Sala delle Asse, monthly hourly cumulative presence and the presence of direct radiation for a representative day during every month.

The textile properties considered are reported below:

- **Type 1**: τ_{vis} 4%, $\tau_{vis,tot\ component}$ 3,6% (glass τ_{vis} 88% + textile);
- **Type 2:** τ_{vis} 28%, $\tau_{vis,tot\ component}$ 27,5% (glass τ_{vis} 88% + textile);
- **Type 3**: τ_{vis} 50%, $\tau_{vis,tot\ component}$ 44,4% (glass τ_{vis} 88% + textile).

The results show that during the period of maximum exposure to the solar radiation and with high availability of natural light, optimal values of τ_{vis} are below 25%-28% to prevent glare, but providing at the same time appropriate levels of illuminance.

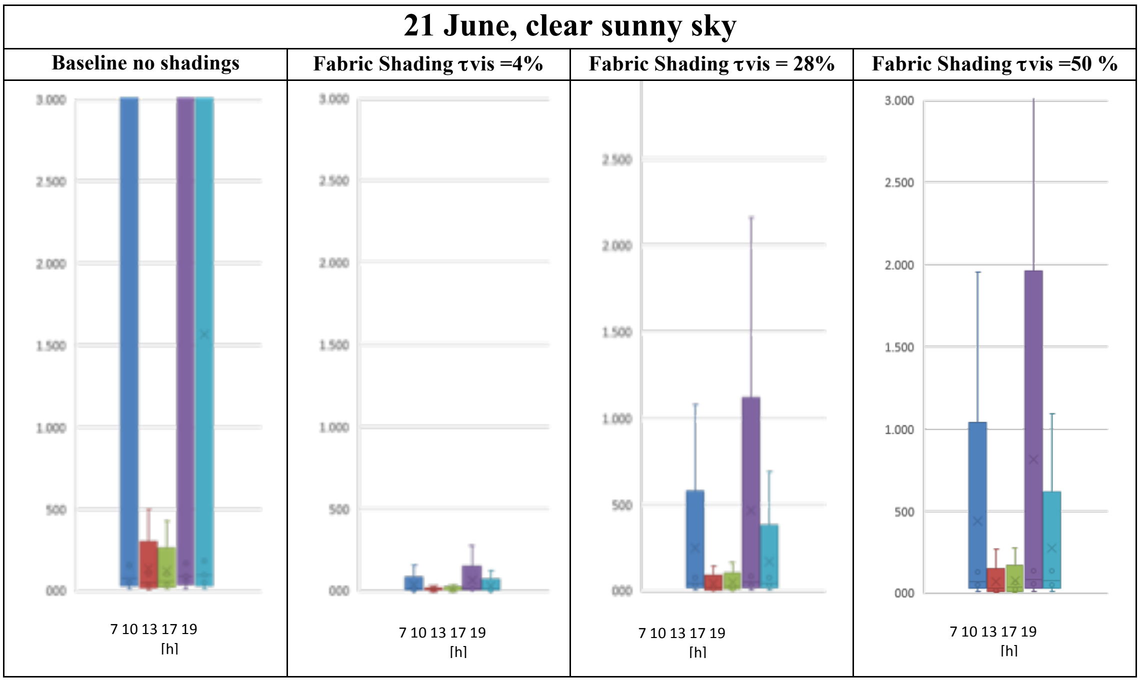


Figure 8: Simulation results for different 21st of June clear sky condition under different shading condition hypothesis: no shade, shade τ_{vis} 4%, shade τ_{vis} 28%, shade τ_{vis} 50%. With a clear sky, the peak value can reach its higher value. The diagrams have the same peak value equal to 3000 lux. The baseline is out of range Despite this, to have comparable results, the axis that shows Lux values has been set with a peak value of 3000 lux. The optimized solutions are textile types 1 and 2.

Optical and radiative properties of the textiles- measurements

Five types of textile samples were tested with different patterns, V/P ratio and colour. Measurements for the determination of light and solar transmittance properties (τv, τe) were performed with a Perkin Elmer Lambda 950 dual beam UV-Vis-NIR spectrometer, equipped with a 150 mm diameter integration sphere (with PMT/PbS detectors). Measurements were made with a resolution of 5 nm, in the spectral range between 250 and 2500 nm. The average curve for each product was calculated, and therefore the values of solar reflectance, UV, visible and NIR reflectance, weighing the curve with respect to the spectral distribution of global solar irradiance on a horizontal plane with air mass equal to 1,5, according to ISO 90501.

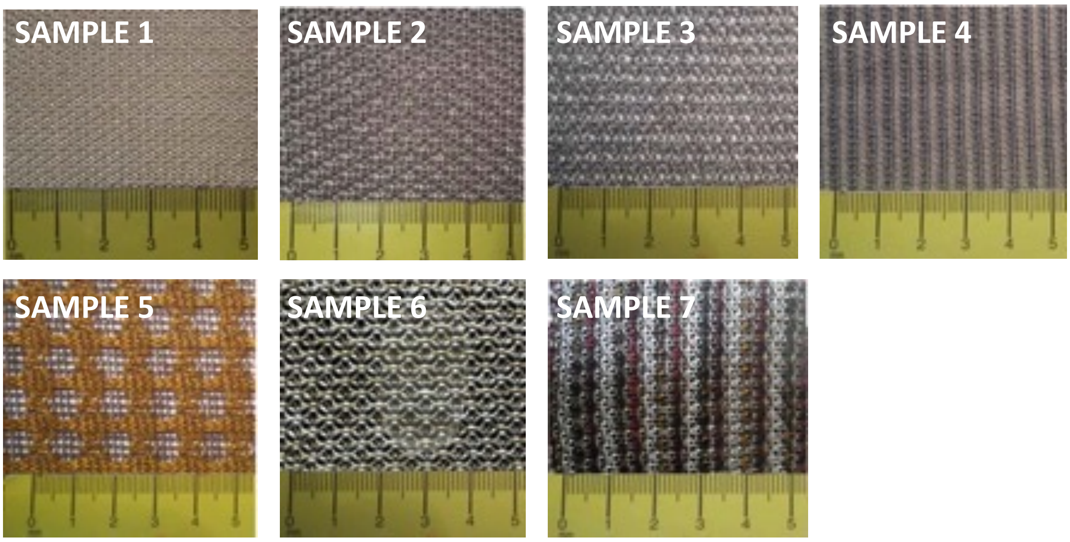


Figure 9: Textile samples (reference: SeedLab.ABC, ABC Dept, Politecnico di Milano). Samples from 1 to 4 are measured in non-tensioned condition and with controlled pre-tensioning. * Samples 1, 2 and 5 were measured, but their results are not shown because of their wide mesh and high variation in the possibility to be tensioned.

In general, measurements for samples with low stretching feasibility have a repeatability and stability characteristic of the result, while for samples with a high degree of deformability, the measurement of transmittance depends on the degree and homogeneity of tensioning of the fabric itself. Below, as an example, are the measurements of the optical properties of some samples stretched and not stretched. As regards light performance, the samples that most effectively satisfy the requirements are Sample 1 and 2, which optimize light performance while simultaneously providing control over the UV component of the radiation. In fact, a sample with the densest and most compact yarn and the thickest texture makes it easier to control the transmission of solar radiation.

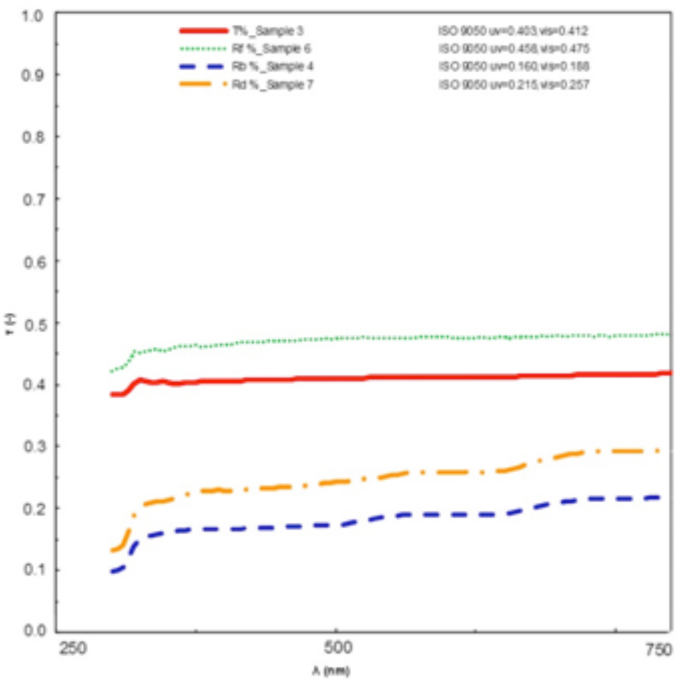
Comparison of stretched with non-stretched samples (3 vs 6 and 4 vs 7)			
Sample number	**τ_{VIS} [%] (ISO 9050)**	**τ_{UV} [%] (ISO 9050)**	
Sample 3	41,2	40,3	
Sample 4	18,8	16,0	
Sample 6	47,5	45,8	
Sample 7	25,7	21,5	

Table 3 – UV and VIS transmittance measurements for selected samples. Perkin Elmer Lambda 950 used as spectrometer (reference: SeedLab.ABC, ABC Dept, Politecnico di Milano).

As regards light performance, the samples that most effectively satisfy the performance objectives declared at the preliminary stage are Sample 1 and 2, which optimize light performance while simultaneously providing control over the UV component of the radiation. In fact, a sample with the densest and most compact yarn and the thickest texture makes it easier to control the transmission of solar radiation.

Solar Radiation mapping and daylight distribution - In situ measurements

In order to validate the simulation procedure and to characterize the performance of the shading devices, a campaign of measurements was carried out in situ, mapping the illuminance levels in accordance with different type of tested shading fabrics. type of shading.

On-site measurements were carried out using the following sensors (Fig. 10):

- Luxmeter T-10 (Standard receptor; measuring range 0,01-299,900 lx);
- Datalogger 4 inputs/M RS232 LSI Lastem;
- Light sensor BSR001 (measuring range 0,01-25 klx).

The use of several sensors has allowed the simultaneous measurement of the illuminance level on both horizontal (O-measurements) and vertical (V-measurements) plane to assess the performance differences of the different textile elementes. The unshaded glazed scenario was considered as a baseline. A preliminary assessment of the measurement procedures was required to align and calibrate the instruments.

Measurement of the illuminance levels in situ were defined for three reference grids (O1 base grid relating to the entire horizontal plane/floor of Sala delle Asse; O2 portion of the grid orthogonal to the NORTH-WEST exposed façade; O3 portion of the grid orthogonal to the NORTH-EAST exposed façade). The three identified analysis grids had all steps of 100x100 cm (size defined in relation to the size of the floor tiles of the room used as a mapping reference). In this way, it was possible to define univocally and in a reproducible way the measurement grid. The total number and distribution of detection points for Horizontal Illuminance were as follows:

- Grid O1: 220 measurement points;
- Grid O2: 27 measurement points;
- Grid O3: 27 measurement points.

The total number and distribution of detection points for Vertical Illuminance were as follows (the limits of which are indicated in the conclusions):

- V1: On the vertical surface wall NORTH-WEST (5 measurement points);

- V2: On the vertical surface wall NORTH-EAST (fresco) (12 measurement points);
- V3: Orthogonal to the window and door frame - NORTH EAST (18 measurement points -1n in case of curtain presence);
- V4: Orthogonal to the window - NORTH-WEST (18 measurement points).

Measurements were made on four days, two of which were consecutive and on Figure 9 an example of the obtained results: Day 1: 05/03/2019; Day 2: 13/03/2019; Day 3: 14/03/2019; Day 4: 21/03/2019.

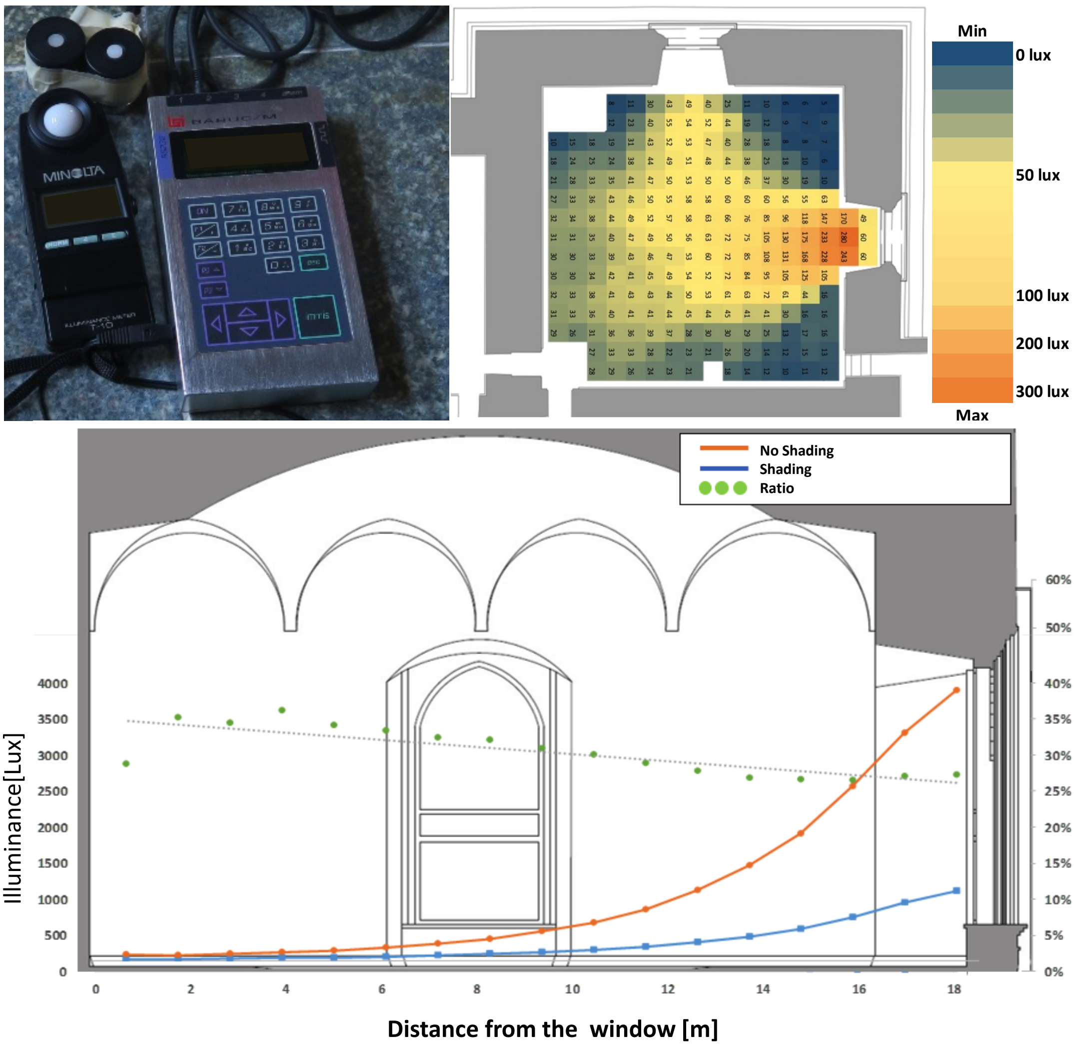


Figure 10: Measuring instruments (top left), mapping of illuminance levels on horizontal surfaces GRID O1 (top right) and cross-sectional trend of illuminances with and without shading (bottom).

The analysis has partially allowed the comparison of the performances of the different shading devices, because of the variable sky conditions during the measurements, that required time to map every single point, but also for some issues related to the change in fabric density when applied over the shading system structure. However, the measurements were used to define a qualitative pattern of lighting to be associated with each type of shading device. A further measuring campaign is ongoing after the installation of final 1:1 demostrators in situ.

Mechanical tests

A pair of textiles were selected from the optical measurements, namely Sample 1, Sample 2, as well as a a further couple of textiles were selected after the first mock up installation, namely Sample 3 and Sample 5. These all went through mechanical testing. All samples use the non-flammable thread, a polyester yarn that is chemically treated to achieve this property (4spaces, 2018).

A limitation of knitted fabrics is the maximum width in terms of production, which depends on the CNC-knitting machine dimension along the weft direction. This can prove to be a challenge when dealing with large-scale projects that require a seamless textile application. For example, Sample 1 and Sample 2 include two different thermo-fixated knitted textiles, that have the same knit pattern, also identified as Lacoste loop-and-tuck piquet knit, but they might hugely differ for strain-stress behaviour and permeability to the natural light. Sample 2 uses a thicker thread and a bigger knitting matrix, in comparison with Sample 1 (Fig. 11). Sample 1 has a matrix unit of 2,1 x 3,2 mm warp-weft and a thread of 0,43mm, whereas the latter has a base unit of 4,5 x 5,5 mm and a thread of 0,81mm. Thus, in Sample 2 the unit and yarn are both scaled up by

90% but its matrix unit is less elongated in weft direction than Sample1's, which makes it slightly denser.

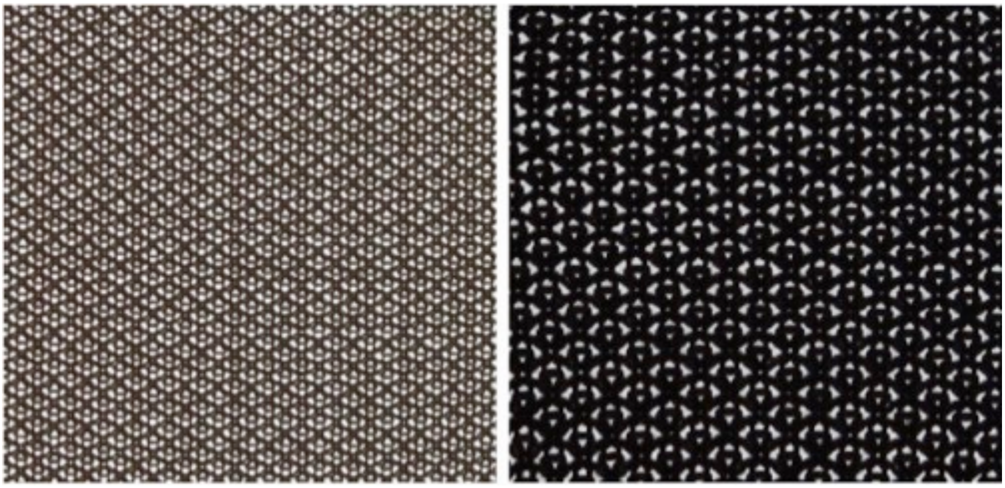


Fig. 11 - Piquet Lacoste pattern of Sample 1 on the left and Sample 2 on the right compared in a backlit 50 x 50 mm sample.

Thus, maximum elastic elongation can inform the feasibility of a designed structure. In this specific case, the project calls for the installation of a 3-meter-wide textile as a window screen. The producer of these knitted textiles defined maximum weft width as ranging between 1,75 and 2,4 meters (4spaces, 2018). This limit is approximately 1 meter shorter than the context and thus, since the objective was to avoid sewn seams for a more uniform appearance, elongation from stretching the fabric needed to be assessed. In this regard, uniaxial and biaxial stress tests were performed. The focus of tensile tests when dealing with coated or woven textiles is the ultimate tensile strength (UTS), whereas this case addresses elastic deformation, both in terms of the maximum load and the corresponding elongation. This consideration came because of the design requirement of making the installation process reversible in order to unmount the fabric, wash it and then reassemble it on site. Even though the topic of knitted fabric testing is recent and unexplored, some important precedents were selected as a basis for the testing methodology.

One of the earliest attempts in uniaxial testing of knitted fabrics was performed on interlock-knit textiles made of a reinforced composite thread (Huang et al., 1999). The applied standard was ASTM D3039M-93, relative to polymer matrix composite materials. The theme of knitted fabric stress testing was only revisited one decade later in the context of material mechanics (Jinyun et al., 2010) and made use of standard ASTM D4964-96 to extract the modulus and Poisson ratio of elastic plain knitted fabrics by applying a series of loading and unloading.

As far as biaxial testing is concerned, the examples of previous research highly differ from each-other. For instance, in (Jinyun et al., 2010) a non-standard method was followed and the samples were cut into square shapes, whereas in the tests performed for the Hybrid Tower project (Thomsen et al., 2016), the samples were cut into cruciform shapes and standard MSAJ M-02-1995 was used. Since this standard is specific to coated textiles, in this case it was applied with the addition of further knit-specific considerations, such as consolidating the edges with an elastic overlock stitch to protect them against unraveling.

In our case, uniaxial stress tests were held according to European standard EN ISO 13934 by first pre-tensioning and then imposing displacement control in a room of temperature 23° C. The clamping system consists of steel clamps that fix the specimen with the help of a rigid steel keder element. Rubber was added as a friction and buffering material to avoid slippage from the metallic clamps and to prevent breakage at the extreme side points.

The uniaxial tests show a similar behavior in Sample 1 and Sample 2 (Fig. 12), whereas Sample 3 and Sample 5 behave more like each-other (Fig. 13).

Sample 1and Sample 2 exhibited a firm behavior and were not prone to unraveling during the first mechanical tests, thus the elastic overlock was not used and the yarns of cut edges were left to act freely. However, in the case of Sample 3 and Sample 5 an elastic overlock was necessary.

Sample 2 however is produced at a 1,75 m width, which according to the tests proves to not be feasible in terms of extension.

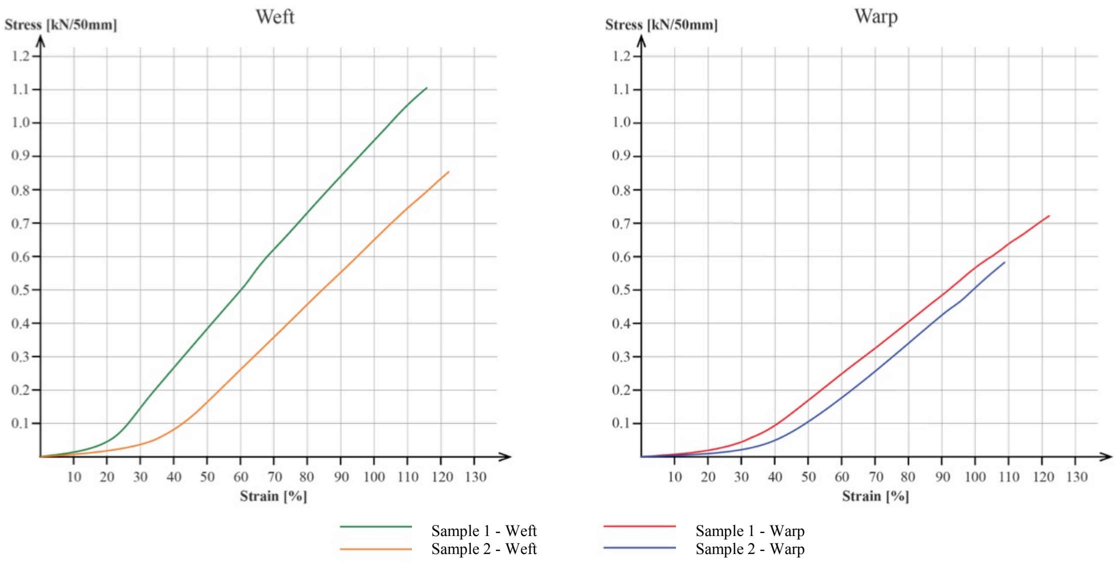


Figure 12: Uniaxial strain/stress graph comparison of Sample 1 and Sample 2.

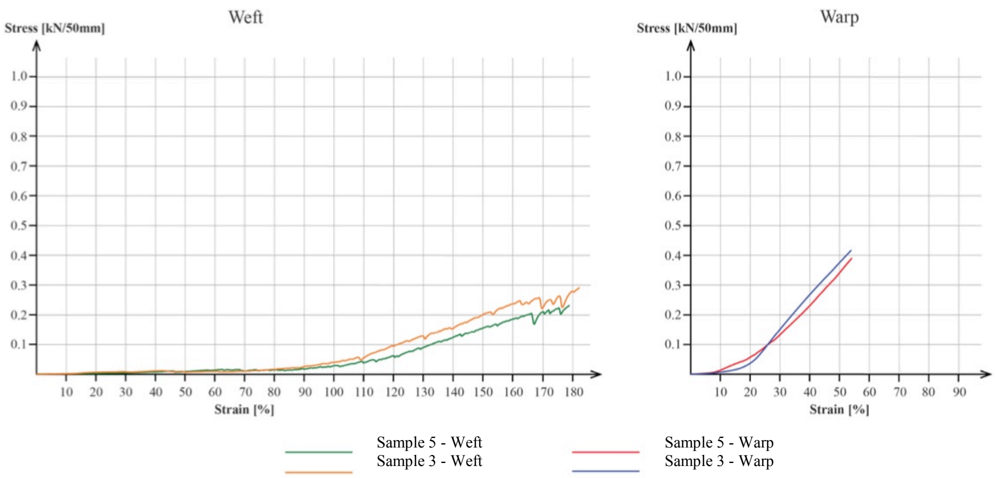


Figure 13: Uniaxial strain/stress graph comparison of Sample 5 and Sample 3.

Biaxial tests were held according to the MSAJ M-02-1995 standard, with a customized load history and clamps for more even load distribution. Due to their tendency to not unravel tested during uniaxial testes, the samples were cut according to standard MSAJ M-02-1995, i.e. in a cruciform shape of 200 x 200 mm as shown in Figure 14.

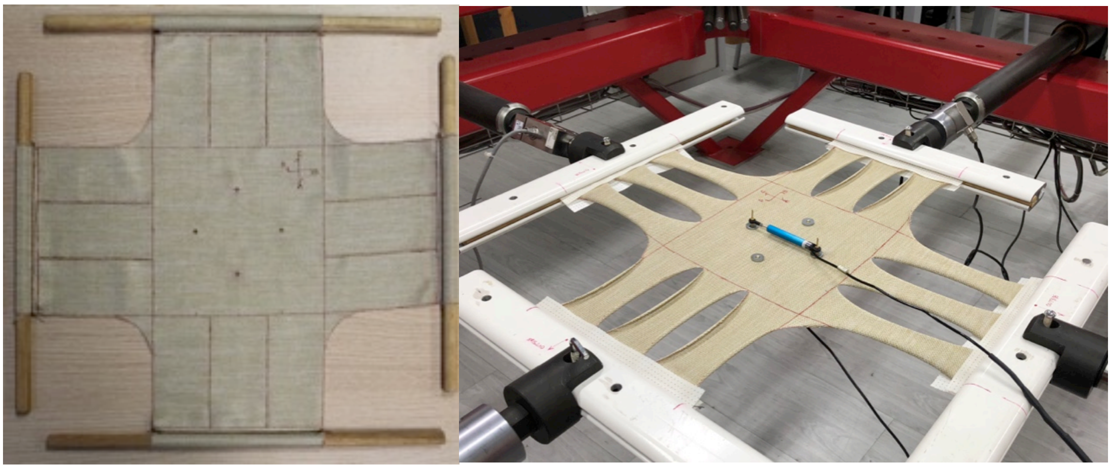


Figure 14. On the left: sample with the keders inserted in the pockets. On the right: the sample placed into the profiles and then attached to the motors. (TAN group, ABC Dept., Politecnico di Milano).

Based on uniaxial tests of the fabrics, the forces were again limited to the first part of the stress/strain graph, specifically to a 21% strain, because of the behavior of the textile that starts to deform in a plastic manner for lower loads than 1/4 of the UTS.

The biaxial load profile consists of four initial cycles for straightening the material similarly to Sample 1, one cycle with a higher load in weft, three cycles of the same load, one cycle with a higher load in warp and finally a plateau in warp. The plateau was added again because of the long-term tensile application of the project.

The biaxial tests revealed another property inherent to knitted textiles, which is their extensive retraction in warp when stretched considerably in the weft direction (Fig. 15).

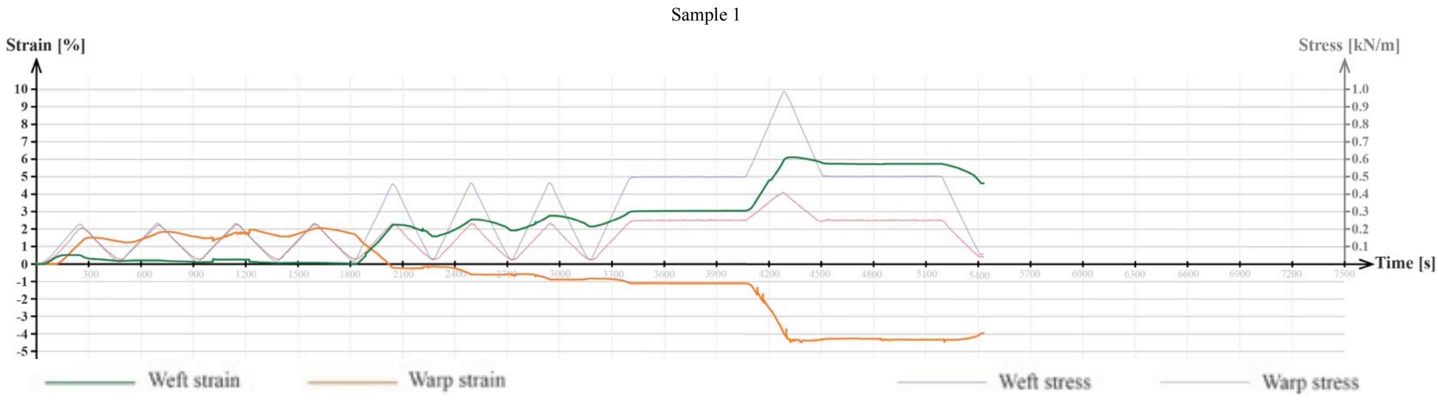


Figure 15: Biaxial strain over time graph of the Sample 1.

A further consideration was made on the design requisite of remounting the structure after maintenance. The ability of the textile to return to its original dimensions after being stretched for a long period of time, as well as the extent to which the fabric shrinks during washing, needed to be evaluated. For this purpose, the Sample 1 was retested with the same corresponding load profiles and it was also washed (water temperature 30° C) to assess the shrinkage of the textile. This procedure is experimental and highly specific to the architectural project, but it was intended to provide insight into the real behavior of the material when dismantled and remounted.

As a conclusion of both mechanical and optical tests, it was decided to discard Sample 2 because of a lack of stretching feasibility, and to also discard Sample 5 due to the intricate substructure that would not block the sun radiation evenly. Finally, Sample 3 will be used for the highest transmittance prototype and the current Sample 1 for the low one. After the tests, the producer agreed to producing a less dense kind of Sample 1, with the aim to meet the requirement of the medium transmittance, in addition to the customised mixed-density fabric, useful to open the following experimental phase of the real-scale prototypes' fabrication and their in-situ installation.

Real-scale prototypes

Two real-scale prototypes were developed and installed, with the aim of widening crucial knowledge on this bespoke textile hybrid screen system. The first one, in scale 1:1,5. The latter, in scale 1:1 was installed at the installator's factory.

The first real-scale prototype consisted of a 1 to 1,5 model, was installed at Textiles HUB Laboratory (fig. 14), while the anemometric, optical, and mechanical measurements were still on-going. It mainly aimed at assessing the behavior of the top arch. Firstly, two vertical C-shaped profiles were anchored on the ceiling and on the ground, which were afterward closed with an L-profile to achieve a pocket to slide the keder in. Then, the reinforcing bar was fixed in the right position by being passed through hooked elements and then secured with cable clamps at its ends. The next step was proceeding to cut the pattern of the textile, using the knitted textile tested as Sample 1. The keders were passed through the vertical edges and GFRP elements in the arched portions. Afterwards, it was proceeded to lifting the textile from the upper GFRP bar, fixing it in the corresponding hooks and connecting it to the reinforcement bar. The textile was then inserted with the help of the keders into the vertical profiles and properly tensioned. This first prototype confirmed the validity of the GFRP cross-section dimensioning coming as a result of computer simulations, which gave diameters of 8 mm for the principal bent rods and 6mm for the reinforcing ones (Kolo, 2018).

The elongation extent of the textile was also confirmed in the horizontal weft direction, but from the prototype it was concluded that there is need for slightly more stretching compensation in the vertical arched portion (fig. 14).

These considerations are then applied to the cutting pattern of the four options that were produced and tested in the further 1:1 scale demonstrator, which was created at the installator’s headquarter, just after the manufacturing of the knitted fabric, to which two thin plastic zips were welded on the long sides (fig 15). This full scale demostrator allowed the authors to optimize the connections between vertical elements and the top and bottom arches, as well as achieving more knowledge on the possible installation issues, which also might depend from the elasticity of various knitted materials.

Fig. 14. The first 1:1,5 scaled prototype tested at Textiles HUB Laboratory, Politecnico di Milano

Fig. 15. The 1:1 scale demonstrator tested at the installator’s factory

Eventually a further set of panels were produced, as Sample 1A - less dense; Sample 1B - more dense and the mixed-density one. They were alternatively installed and tested in situ, firstly in Sala delle Asse in March 2019 (fig. 16) and later in Sala del Gonfalone, where a new measurements campaign started in May 2019 and is still on-going (fig. 17).

Fig. 16: First full-scale mock up installed in Sala delle Asse at Castello Sforzesco, March 2019. On the left: screen made of Sample 1. On the right: detailed view of the screen made of mixed-density membrane.

Fig. 17 Current experimental installation of two screens at Sala del Gonfalone, Castello Sforzesco. The textile panel tested on the right side window is made of Sample A1 (less dense), while that on the left side of the room is made of Sample A2 (more dense).

Conclusion

In conclusion, this paper proposes an integrated feedback process instead of the usual linear one that is commonly applied in the architectural practice.

The developed multidisciplinary workflow helped to refine the project proposal in advance, in order to provide a more context-aware solution, which could target the design requirements and the different aspects of comfort at the same time, as opposed to an evaluation post-proposal. The anemometric measurements guided the design towards a mixed-density alternative, which would not be considered without tests, showing that the most humid areas were located in the borders of the windows. The optical measurements helped to define the desired transmittance and the knitting requirements. Finally, the mechanical studies gave crucial information on the selection the textiles and their compensation values for the final installation process.

A bespoke solution is designed, which challenges also the way the manufacturing and installation industry is organized, since currently it is largely based on standard solutions. In addition, the paper argues that the expertise exchange between professionals from different fields is more efficient at an early stage of the design process and the presented methodology can be potentially applied in all the historical contexts.

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