

Proceedings of the TensiNet Symposium 2019

Softening the habitats | 3-5 June 2019, Politecnico di Milano, Milan, Italy
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A tensile screen for the windows of Castello Sforzesco: integrating anemometric, optical and mechanical tests in the early-stage design of bespoke textile hybrid structures in historical contexts

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Abstract

This paper presents an interdisciplinary methodology of implementing bespoke, low-impact, lightweight structures as additions to historical buildings with the aim of enhancing their performance in terms of visual, lighting and hygrothermal comfort. To do this, the study focuses on the renovation of Sala delle Asse, one of the most relevant rooms of Castello Sforzesco in Milan. The design task at hand is to produce self-standing vertical screens for the large-scale windows in the room, in order to reduce the amount of sunlight that reaches the frescos, as well as to block air drafts that bring 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 in the borders, but no perforations are allowed on the vaulted edges of the windows. Thus, a textile-hybrid structure is proposed as a solution, due to its self-standing principle that would not require drilling on the vault. The experimental campaign starts by performing preliminary anemometric measures on the room and by modelling the illuminance level based on the definition of the optical properties of the glazing surfaces. These analyses, combined with parametric simulations, gave results on the preferred position and optical requirements of the curtains.

DOI: [10.30448/ts2019.3245.34](https://doi.org/10.30448/ts2019.3245.34)

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Peer-review under responsibility of the TensiNet Association

After a selection of materials with the right visual qualities was made, these textile materials went through further optical tests to check their compatibility with the comfort requirements. Design choices were updated with these test results and were followed by mechanical studies on the stretching properties of the unconventional knitted textile materials to define the project's feasibility. This feedback loop of empirical data, in addition to a computational simulation of the structure's behavior, was applied to the construction of a real-scale mock-up to test the bending active principle. The mock-up also gives experimental results on how to change the structure in further design steps. In conclusion, this paper proposes an integrated feedback process, started from the very early-stage of design, that is not commonly applied in the architectural practice. In addition, the paper argues that the presented methodology and design process can be potentially applied in further historical contexts.

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

1. Introduction

One of the challenges that contemporary applications of membrane structures face today is the way they can improve the attributes of the built environment. This paper explores a specific potential application of ultra-lightweight architecture to one of the most important listed historical buildings of Milan, Italy, with the aim of 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.

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, 2000. In the case of the Olavinlinna Castle, the lightweight structure was installed and dismantled recurrently throughout its lifespan. The permanent membrane canopy for the Vienna City Hall gives an even better example of how the potential of retractability was exploited to provide a flexible solution that can be adapted seasonally (Koch, 2004). Both these notable case studies show that membrane architecture is highly compatible with historical buildings, which require a careful and non-invasive approach when it comes to contemporary interventions.

In this paper, the project's context is Castello Sforzesco, a castle initially built by the Duke of Milan, Francesco Sforza, in 1452 and later rebuilt by architect Luca Beltrami in 1893. In the light of the restoration of Leonardo da Vinci's frescos in Sala delle Asse (Fig. 3), there was a need to install window curtains on the two 6-meter-high and 3-meter-wide windows of the room. These 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 office BBPR, which adds to their historical value. Thus, the requisite that became a priority for the project was the one of minimal impact on the surroundings and drilling as few perforations as possible on the walls. This room is located on the first floor of the Falconiera tower on the north-east corner of the castle (Fig. 1), one of the windows facing north-east and the other north-west (Fig. 2). The windows are similar in shape and dimension, but given the historical context, they are not identical. Thus, the idea of a flexible hybrid structure emerged, one that could be adjusted on site at the phase of installing it, in order to adhere to the wall inconsistencies and be fixed with the help of bending-active elements. This was also thought as a solution to the maintenance requirement of dismantling the structure and transporting it easily outside for proper textile cleaning (given that the doors of the castle are very small, the option of a rigid frame would make this process more difficult).

Hybrid structures have been widely explored in 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. The main structural types were limited to section-active, vector-active, surface-active and form-active structures (Engel et al., 1997). Bending-active and hybrid structures are later classified by Lienhard (2014), defining their 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 combination two other complementary structural systems. Textile hybrid structures 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



Figure 1: the Falconiera tower and its affected windows.

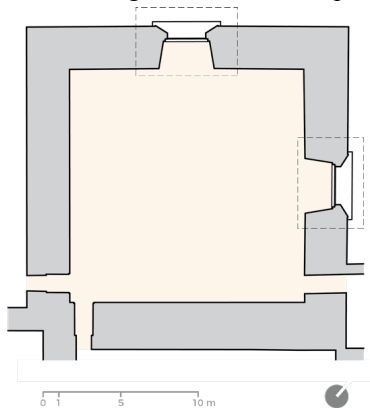


Figure 2: Floor plan of Sala delle Asse, that shows the orientation and location of the windows



Figure 3: On-site photo of the current restoration works in Sala delle Asse

started with (Lienhard, 2014). The first notable precedents in terms of textile hybrid structures came as a result of the research of 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 is the first CNC-knitted fabric with a structural differentiation, aiming to optimise the stretchable fabric for maximum tensile strength and obtain the desired form (Ahlquist, 2014).

However, the most architectural examples in the category are the hybrid gridshell prototype by 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 GFRP rods and computational analysis to produce a self-standing structure reaching a height of 9 meters (Thomsen et al., 2016).

The project 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. 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.

2. Design requirements

The project for the window screens posed a challenge because of the many design requirements to fulfil, some of which being in conflict with each-other. These requirements were emphasized by the Castello Sforzesco officials that are in charge Sala delle Asse's cultural heritage, thus had to be respected to the largest extent. Firstly, the window screens must provide shading for the room and frescos, but it was crucial to have a visual connection to the surroundings of the castle and the Sempione Park, because the room will be used as part of the museum. 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. This factor was significant also because the 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 artefacts. In addition, humidity and air drafts are a major problem of the room because of the poorly performing window frames that date back to 1954, but that cannot be replaced since

they were designed by BBPR and thus carry a historical value. In order to tackle the humidity and especially the air draft problem, the new curtain structures would have to be sealed 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. This is where textile hybrid structures started to be consolidated as a solution.

3. Multidisciplinary approach

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 design product.

The preliminary campaign started by performing anemometric measures on the current conditions of the room and by modelling the illuminance level based on the definition of the optical properties of the glazing and of the internal and external surfaces. These analyses, combined with parametric simulations of optimized solar transmittance values, gave results on the preferred position and optical requirements of the window screens. 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 polyester 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. The mock-up is also seen as an element of the loop, which gives experimental results on how to change the structure in further design steps.

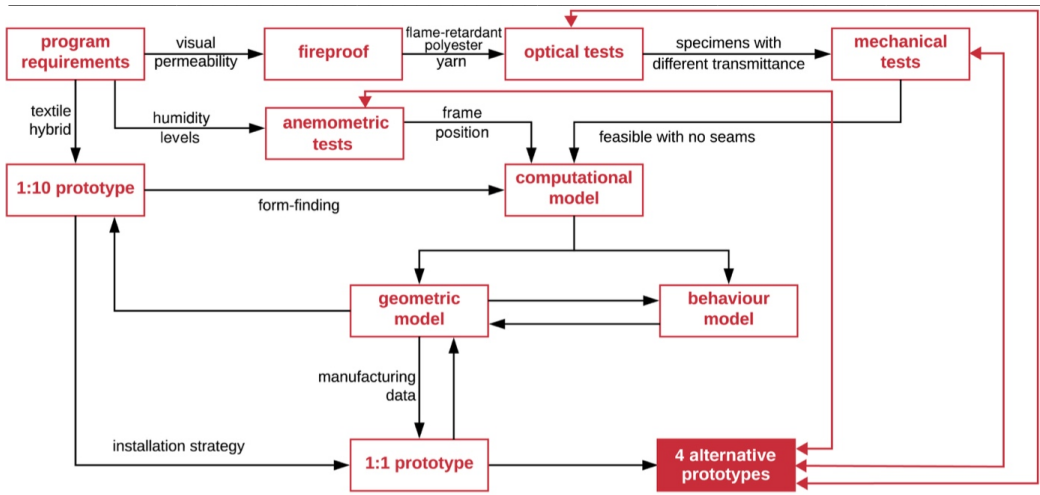


Figure 4: Flow chart of the various competences involved in the project, showing the feedback loop of their interaction; black arrows show exchange that was already applied, while red arrows show future exchange

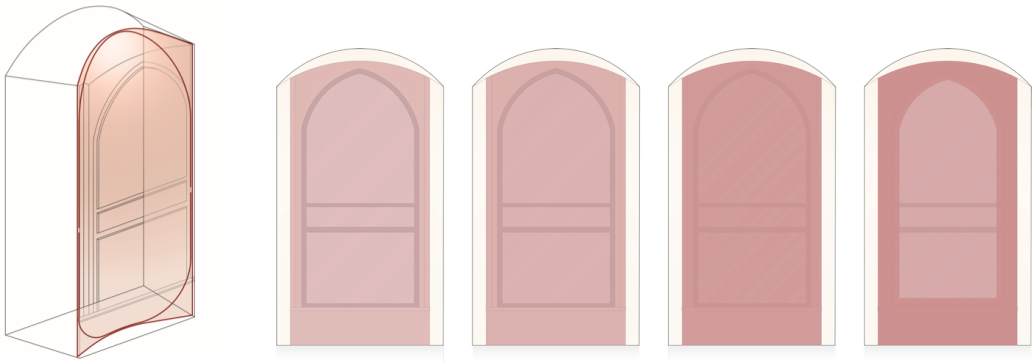


Figure 5: Shape of the bending-active self-standing structure and the 4 alternative prototypes to be tested

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, that will let more light in the room, given its northern orientation (Fig. 5).

4. Experimental testing campaign and modelling

4.1. Anemometric measurements

After an extensive restoration few years after World War II, Sala delle Asse went under few maintenance interventions. Since 2010, the conservators of Castello Sforzesco, in addition to the department of the Galleries of the Municipality, have led an articulated and well-supported program of study, analysis and research involving several Institutions for conservation research and for cultural heritage restoration, with the aim of achieving the best understanding, the most suitable project of conservation and finally, the restoration of the frescos. One of the results of these investigations attributed the main cause of damage to the microclimatic unbalance and the diffusion of soluble salts (Rosina et al., 2017). Microclimatic monitoring has been performed by probes (hourly rate of data recording), psychrometric mapping of the hall and surrounding rooms (every three months for one year and half), anemometric measures in the square areas of about 3x5 m close to the windows (different weather condition: with high speed wind, different direction of the wind, etc). The climate was monitored (T°C and RH, direction and speed of wind) with probes installed on the top of the tower that hosts Sala delle Asse. All the acquired data were processed, plotted and scaled on the plan, with the aim of overlapping the microclimatic map representing the recorded data with the geometric map of the Sala. The aim was to connect the recorded changes in balance with the location of openings in the hall.

4.2. Lighting Modelling and Optical measurements

The objective of the analysis was twofold and provided the input for the research and selection of the types of technological fabrics and their optical-radiative properties. In particular the main intent was retaining the availability of natural light and ensuring the most appropriate quality of light, and, on the other hand, controlling the direct and diffuse radiation (hourly variation) in order to prevent glare and damage of Leonardo's frescoes and the decorated vault.

The mean illuminance (lux) on the horizontal and vertical surfaces, the distribution of the illuminances (% area with illuminance <100 lux; % area with illuminance between 100lux and 2000lux; % area with illuminance >2000lux) and the occurrence of direct radiation have been considered as parameters for the analysis of the effectiveness of the shading systems.

Modelling has been performed for days with maximum and minimum incidence of radiation (summer and winter solstice). Our reference test case was the Sala delle Asse without the application of textile element in correspondence of the window. The light transmission of the glass and the reflectance of the internal surfaces was known or was considered according to scientific literature.

4.2.1. Solar Radiation mapping

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 twenty-first for each month.

This analysis has shown that in this particular day the surfaces with Leonardo's frescos are never affected by direct radiation; on the contrary, they are the less illuminated surfaces.

4.2.2. Daylight Modelling

A parametric approach has been adopted for modelling the availability of natural light. The variables considered have been: a) the sky conditions (cloudy and Clear sunny); b) the visible transmittance of textile (3 macro-categories); c) the componet glass + fabric shading performance. The position of the fabric has been considered constant (inner). This parametric analysis has allowed to identify the threshold of textile optical properties (effectiveness) and it considered as a preliminary benchmark to reduce the selection of the textile samples and whose optical performance was to be measure. The textile properties considered were below reported:

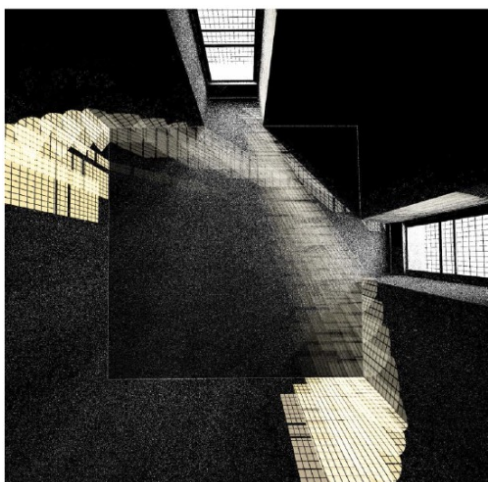


Figure 6: Top view of the Sala delle Asse and the presence of direct radiation, June 21, 4 am - 9 pm.

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 of the radiation and availability of natural light in the environment the optimal values of T_{vis} are below 25%-28% to prevent glare and to provide appropriate levels of illuminance (with direct radiation).

4.2.3. Material and experimental test

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 (τ_v , τ_e) 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. Additional measurements were made to identify for some samples: a) the influence of stretching feasibility

on the solar transmittance measurement; b) the influence of the orientation of the fabric with respect to measuring port (0° and 90°). (Table 1). Some samples were excluded because of the type and size of the texture. In these cases, the ratio between the geometry of the yarn (texture) and the characteristic size of the light source of the instrument did not allow to obtain a significant measure of the material properties. For all large textures, other measurement techniques must be used (sample 5, 6 and 7).

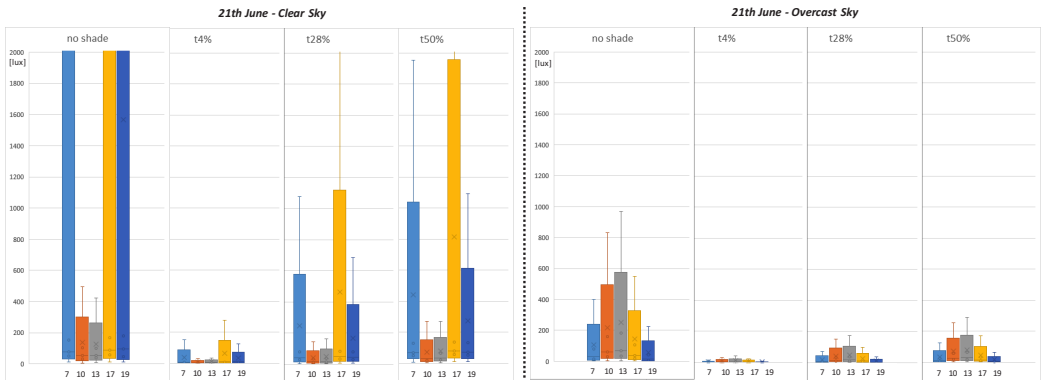
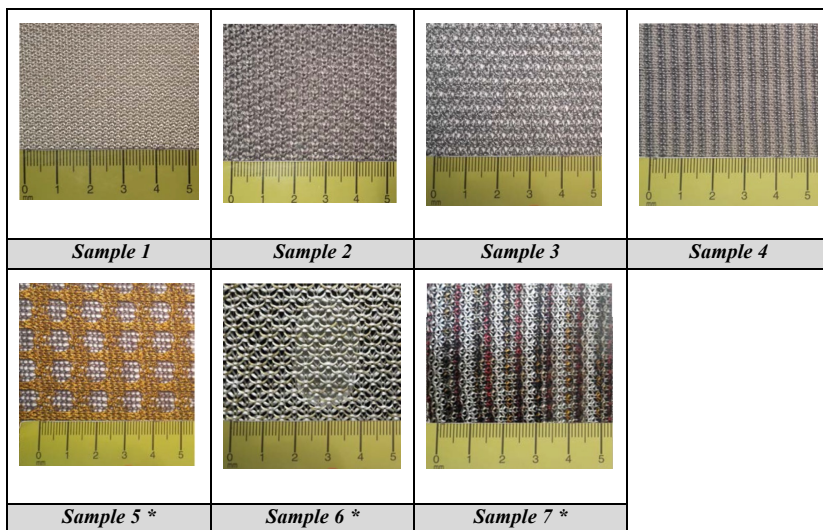


Figure 7: Simulation results for different 21th of June sky condition (clear and overcast sky) with different shading condition hypothesis: no shade, shade τ_{vis} 4%, shade τ_{vis} 28%, shade τ_{vis} 50%. With a clear sky, the peak value can reach higher value. Despite this, to have comparable results, the axis that shows Lux values has been set with a peak value of 2000lux. The optimized solutions are textile type 1 and 2.

Table 1: 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. * Sample measured, but results are not shown because of their wide mesh and high variation in 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.

Table 2: UV and VIS transmittance measurements for samples 1, 2, 3 and 4.

Sample number	τ_{VIS} [%] (ISO 9050)	τ_{UV} [%] (ISO 9050)	Comparison of stretched with non-stretched samples
Sample 1	27.6	21.7	<p>The graph plots transmittance τ (y-axis, 0.0 to 1.0) against wavelength λ in nm (x-axis, 250 to 750). It compares four samples (1, 2, 3, 4) in both stretched (solid lines) and pre-tensioned (dotted lines) states. Sample 3 (black) has the highest transmittance, followed by Sample 4 (blue), Sample 2 (green), and Sample 1 (grey). Pre-tensioned samples generally show higher transmittance than their stretched counterparts, especially in the UV range (250-400 nm).</p>
Sample 1 pre-tensioned	28.2	22.3	
Sample 2	14.7	13.1	
Sample 2 pre-tensioned	16	14.7	
Sample 3	41.2	40.3	
Sample 3 pre-tensioned	47.6	47.1	
Sample 4	18.9	16.4	
Sample 4 pre-tensioned	25.8	22.0	

4.3. Mechanical tests

The textiles that were selected from the optical measurements, corresponding to Sample 1, 2, 3 and 5, went through mechanical testing. A limitation of knitted fabrics is the maximum width in terms of production, that depends on the CNC-knitting along the weft direction. In large-scale projects, the maximum elastic elongation can inform the feasibility of a designed structure. The specific project calls for the installation of a 3-meter-wide textile screen, while the selected knitted textiles are produced with a weft width ranging between 1.75 and 2.4 meters (4spaces, 2018). A further objective was to avoid sewn seams for a more uniform appearance, controlling

elongation precisely. In this regard, uniaxial and biaxial stress tests were performed, focusing on the elastic deformation, in order to achieve the requirement of reversible installation and 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), applying the standard ASTM D3039M-93. As far as biaxial testing is concerned, the examples of previous research highly differ from each-other. For instance, square shaped samples were tested following a non-standard method (Jinyun et al., 2010), whereas in the Hybrid Tower project (Thomsen et al., 2016), the samples were cut into cruciform shapes and standard MSAJ M-02-1995 was used. In this case the same standard was applied, but consolidating the edges with an elastic overlock stitch to protect them against unravelling of knitted material.

Based on these precedents, uniaxial stress tests were held according to EN ISO 13934 and biaxial tests were held according to the MSAJ M-02-1995, with a customized load history. Samples 1 and 2 exhibited a firm behaviour and were not prone to unravelling during the first 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 5 an elastic overlock was necessary. Biaxial tests were applied a customized load history, since uniaxial tests showed that 1/4 of the ultimate tensile strength (UTS) resulted to be too high, because in this portion of the stress/strain graph knitted textiles already reach a considerable irreversible deformation. Uniaxial tests show a similar behaviour in Sample 1 and 2 (Tab. 4), whereas 3 and 5 behave more like each-other (Tab. 5). As sample 2 is produced at a 1.75m width, the tests proves its limited extension. Furthermore, the biaxial tests revealed another property of knitted textiles, which is their extensive retraction in warp when stretched considerably in the weft direction (Tab. 3).

As a conclusion, Sample 3 will be used for the highest transmittance prototype (T_{vis} when tensioned 47.6 %) and Sample 1 for the low one (T_{vis} 27.6 %). A less dense version of Sample 1 was also produced for the medium transmittance one, in addition to the customised mixed-density fabric. This proved to fall in the right range between Sample 1 and 3 (T_{vis} 38.9 %), while it will go through the testing loop again to assess its mechanical properties.

Table 3: Biaxial strain over time graph of Sample 1
Ogliastra A1

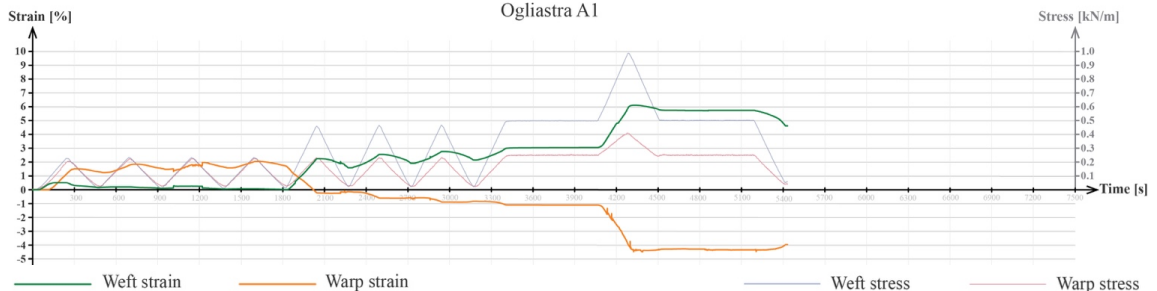


Table 4: Uniaxial strain/stress graph comparison of Sample 1 and 2

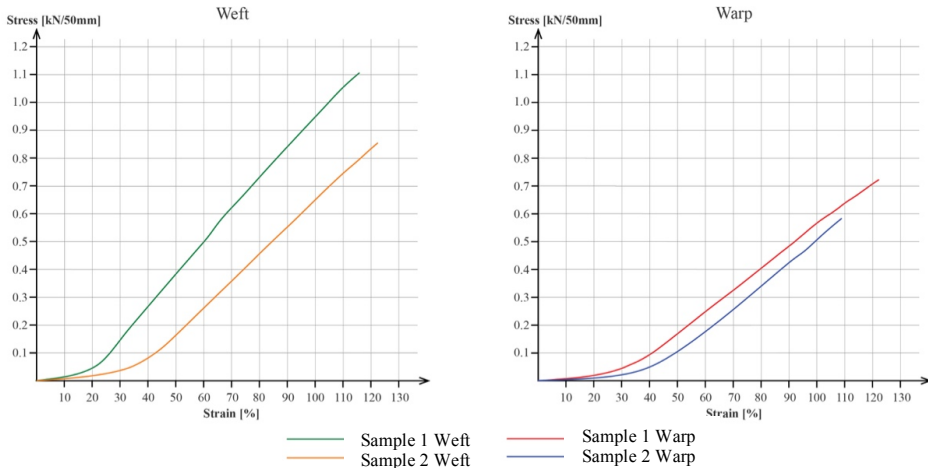
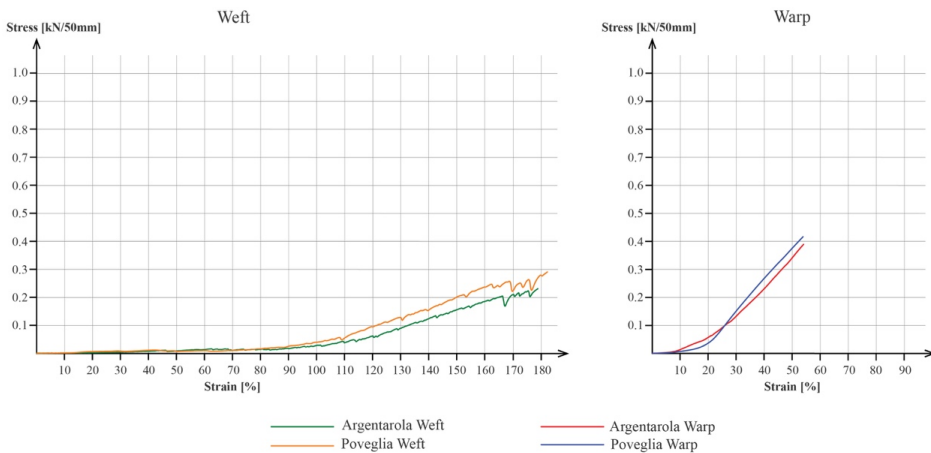


Table 5: Uniaxial strain/stress graph comparison of Sample 3 and 5



5. Real-scale prototype

The real-scale prototype consisted of a 1 to 1,5 model and it 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 afterwards 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 cutting the pattern of the textile, using 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. The 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. 8) These considerations are then applied to the cutting pattern of the four options tested on site (fig. 9).

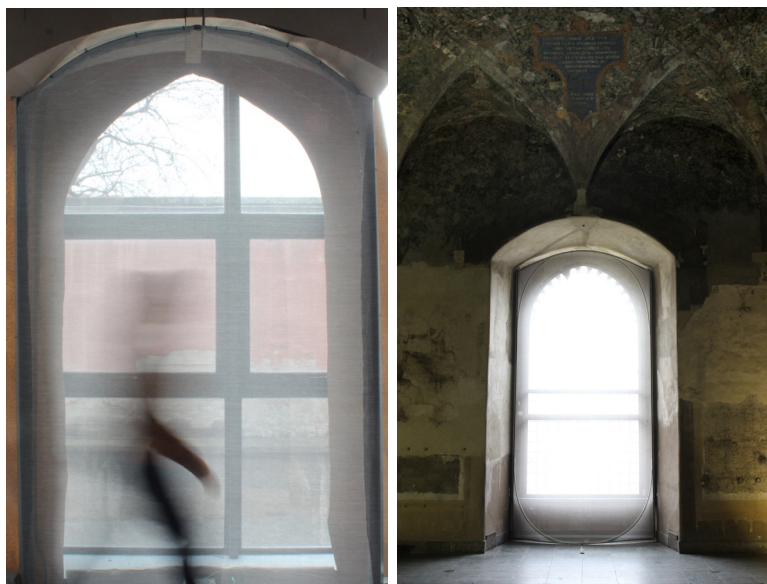


Figure 8 (left): Assembly process of the prototype in Lab.

Figure 9 (right): first full-scale prototype installed in Sala delle Asse at Castello Sforzesco.

6. Conclusion

The developed multidisciplinary workflow helped refine the project proposal in advance, in order to provide a more context-aware solution, that 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, that would not be considered without the tests showing that the most humid areas were located in the borders of the windows. The optical measurements helped 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.

Acknowledgements

We express our gratitude to the Director of the restoration works, Dr. Arch. Michela Palazzo, and to the Director of the Art Archives at Castello Sforzesco, Dr. Arch. PhD. Francesca Tasso, for giving us the opportunity to tackle a project in such an important context of cultural heritage. We would also like to thank all the suppliers which supported us during the materials' choices: 4spaces, Giorgio Piovano Home Textiles, and Eos Design.

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