Design-driven Uniaxial and Biaxial Tensile Testing of Knitted Fabrics Applied to Construction

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Abstract

Knitted fabrics are rarely subjected to tensile stress tests in the field of architectural construction materials, mostly due to their common use as drapery. However, recent non-standard applications of tensioned knitted textiles to hybrid lightweight constructions call for the assessment of their mechanical behavior. In the light of the absence of specific testing methodologies regarding knitted fabrics in the field of construction, this study aims at investigating customized testing techniques that target design requisites, as well as extending previous groundwork on plain weft-knitted textiles to tuck-loop knit structures. Fabrics with a piquet Lacoste loop structure are tested uniaxially and biaxially in order to estimate the feasibility of a relatively large-scale project. The challenging task consists of stretching the limited production width in weft direction to the extended dimensions of the tensile architectural project. Hence the study focuses on elongation limits and especially on the maximum elongation that allows elastic deformation. Extracted empirical data are expressed in the form of stress/strain curves that enable an appropriate understanding of the textiles' mechanical behavior. This inquiry points out the extent to which knit pattern favors directional elongation in warp as opposed to weft or vice-versa. In addition, it addresses the mechanical performance of knitted textiles by means of a strategic customization of tensile tests that can make them better at informing the design process and feasibility assessment.

Keywords: Knitted fabric, mechanical behavior, uniaxial test, biaxial test, elongation, piquet Lacoste, feasibility, tensile architecture.

1 Introduction

Knitted textiles have traditionally been used in the field of architecture, especially in interior design, in the form of small-scale draperies. This use came because of the ability of their textile alternatives, i.e. coated and woven fabrics, to provide higher rigidity and waterproofing in tensile large-scale structures. There have been however some attempts in the last decade to integrate knitted textiles in larger hybrid structures, mostly combined with bending active elements. These trials have exploited the high customization potential of the fabrics, both density-wise to structurally optimize them [1-5] and appearance-wise [6,7], as well as their ability to stretch to a high extent [8]. The high degree of flexibility of these form-active textiles is complementary to the internal bending-active forces inside fiber-reinforced elastic bars [1-3,6-8] or pneumatic elements [4,5], a mechanical behavior that cannot be replicated by stiffer coated or woven textiles.

Such recent developments call for an appropriate tensile testing method that would be useful to assess not only permissible loads, but also other more relevant properties to the actual application of knitted fabrics, for example maximum elongation and elastic deformation. The current applications of knitted textiles are in the context of research on computational architecture and thus calculate their mechanical behavior by an iterative or computer-aided analysis only [1-6,8]. The first case in which biaxial tests were carried out was Hybrid Tower (an architectural result of conducted research) [7], which had to be placed in a real context with challenging environmental conditions, such as extreme wind and rain. Thus, stress testing is mandatory whenever there are safety standards to achieve and prerequisites relative to the context to fulfill. This is however not easy to be applied to knitted fabrics because of the lack of tensile testing standards specific to these textiles, applied in the field of construction.

Another limitation of knitted fabrics continues to be the maximum width in terms of production that 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. Thus, maximum elastic elongation can inform the feasibility of a designed structure. In our specific case, the refurbishment project for one of the most important listed historical buildings in Milan, Castello Sforzesco, called for the installation of a 3-meter-wide textile as a window screen. 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 fulfilling this standard. The producer of these fireproof knitted textiles defined maximum weft width as ranging between 1.75 and 1.9 meters [9]. This limit is approximately 1 meter shorter than the context and thus, provided that the objective is to avoid sewn seams, elongation from stretching the fabric needs to be assessed.

In this regard, uniaxial and biaxial stress tests were performed on the samples provided by the producer. The focus of tensile tests when dealing with coated or woven textiles is the ultimate tensile strength (UTS), whereas this study on knitted fabrics addresses elastic deformation, both in terms of the maximum load and the corresponding elongation. This consideration came because of an important maintenance design requirement, which was to make the installation process reversible in order to unmount the fabric, wash it and then reassemble it on site. Due to the experimental process of the design and installation, the definition of the prestress in the assembling stage was non easy to be defined and this is an important aspect to be optimized, in terms of exploiting better the material properties. It will be considered in the future developments of this application. Even though the topic of knitted fabric testing is recent and unexplored, some important precedents in research supported our study. In these selected cases, given the lack of standards for knitted textiles, other existing standards valid for uncoated or coated woven textiles were used.

One of the earliest attempts in uniaxial testing of knitted fabrics was performed on interlock-knit textiles made of a reinforced composite thread [10]. Thus, the applied standard was ASTM D3039M-93, relative to polymer matrix composite materials [11]. Even though this provided a supporting base for our considerations on which testing standard to use, composite reinforced threads combined with an interlock knit structure made the referenced textiles considerably robust in comparison to the textiles in our disposal and thus further supporting research had to be considered. The theme of knitted fabric stress testing was only revisited one decade later in two contemporary studies. The first one was conducted on biomedical interlock-knitted fabrics [12] where uniaxial tests were performed according to the standard ISO 7198:1998, that is focused on cardiovascular implants and thus specific to the field of medicine and not construction [13]. The second case was set in the context of material mechanics [14] and made use of standard ASTM D4964-96 to extract the modulus and Poisson ratio of elastic plain knitted fabrics [15] by applying a series of loading and unloading because of the elastic nature of the textile.

As far as biaxial testing is concerned, the examples of previous research highly differ from each other. For instance, in two cases [14,16] a non-standard method was followed and the samples were cut into square shapes, whereas in the tests performed for the Hybrid Tower project [17], the samples were cut into cruciform shapes and standard EN 17117:2018 was used. Since this standard is specific to coated textiles [18], in this case it was applied with the addition of further knit-specific considerations, such as consolidating the edges with elastic overlock stitch to protect them against unraveling. Only this reference made use of the EN standard in loading the samples, whereas the two other studies do not state the load profile that they applied in the biaxial tests. This topic is open for vast studies in the future that could customize and maximize the efficiency of sample loading in biaxial tests, especially regarding materials that remain purely elastic for a very limited amount of elongation, such as knitted fabrics. A first attempt at this customization is made by this study while keeping in mind the design requirements, feasibility and loads that the structure will endure during its lifecycle.

2 Materials and methods

Firstly, uniaxial tests were carried out to investigate elongation in weft and in warp direction separately, mostly because weft strain was more relevant to the research, but also to define a reference for the calibration of further biaxial test loading. Even though the fabric is supposed to be tensioned in both directions, the warp-wise length is unlimited and thus it can be assumed that it will be tensioned only in a fair amount that is necessary to avoid wrinkles. Contrary to the latter, weft stretching will be exploited to the maximum possible strain that allows elastic deformation, since the structure for the abovementioned project also needs to be dismantled for maintenance and plastic deformation will not allow remounting.

However, if weft elongation is not to be considered in an absolute manner as above, biaxial elongation would seem more appropriate. This is the actual case in real-life fabric behavior, especially because the textile will extend much less in weft direction if it is already being pulled in warp and vice-versa. The drawback of this testing method is that the only existing standard for textile biaxial stress testing, MSAJ M-02-1995, does not list knitted textiles in its guidelines. Moreover, since it focuses on coated fabrics, the load profile to be applied by this standard, which defines the maximum load as 1/4 of the ultimate stress, is highly specific to such fabrics due to their linear elastic behavior. According to previous research, knitted textiles highly differ in this aspect, as they deform in a purely elastic manner only in the initial part of the stress/strain graph where the slope does not change, often confined within a range between 1 and 2 % strain [19]. Keeping these considerations in mind, both uniaxial and biaxial tests were applied to the two different knitted textiles in an attempt to simulate the mechanical behavior as closely as possible to the use of fabrics in the real project.

2.1 Employed materials

All samples use the nonflammable thread Trevira®, a polyester yarn that is chemically treated to achieve this property and thus exhibits a sturdier behavior as opposed to usual softer threads used in knitting, but still not reaching the levels of reinforced composite yarns [20]. Flame retardancy was one of the main requisites to fulfill since the beginning of the project, given the importance of the historical artifact and the focus of national architectural practice on safety regulations.

The provided samples include two different thermo-fixated knitted textiles, Ogliastra and Levanzo [9], that have the same knit pattern, also identified as Lacoste loop-and-tuck piquet knit [21]. The latter uses a thicker thread and a bigger knitting matrix, comparison that is shown in Figure 1. Ogliastra has a matrix unit of 2.1 x 3.2 mm warp-weft and a thread of 0.43mm, whereas Levanzo has a base unit of 4.5 x 5.5 mm and a thread of 0.81mm. Thus, in Levanzo the unit and yarn are both scaled up by 90 % but its matrix unit is less elongated in weft direction than Ogliastra's, which makes it slightly denser.

2.2 Uniaxial tensile testing

Uniaxial stress tests were held according to European standard EN ISO 13934 by first pretensioning 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. Three tests were performed in both weft and warp for each fabric to achieve more accuracy, resulting in twelve tests in total. Every sample was cut to a width of 50 mm and an initial length of 200 mm, with an additional 100 mm in length from both sides to provide a grip for the clamps, thus resulting in samples of 50 x 400 mm, as shown in Figure 2.

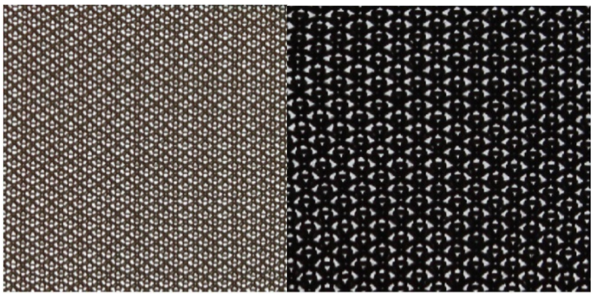

Figure 1. Piquet Lacoste pattern of Ogliastra on the left and Levanzo on the right compared in a backlit 50 x 50 mm sample

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. In each of the twelve assigned identifying codes, OF stands for Ogliastra Fill, LF stands for Levanzo Fill, OW stands for Ogliastra Warp, LW stands for Levanzo Warp, and A, B, C, D, E, F stand for each of the 6 samples tested in weft and then the same letters are repeated for warp. As both textiles exhibited a firm behavior and were not prone to unraveling during the first tests, the elastic overlock, as referenced in [17], was not used and the yarns of cut edges were left to act freely.

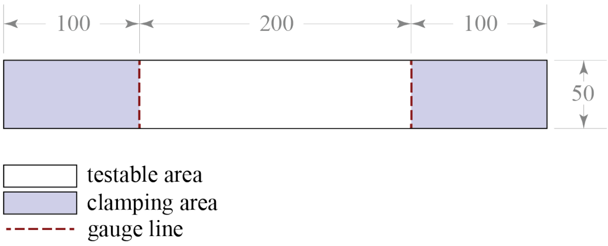

Figure 2. Illustration of cut sample dimensioning

2.3 Biaxial tensile testing

Defining the way to perform biaxial stress tests on knitted fabrics was less straight-forward than uniaxial tests, especially because of the lack of testing standardization specific to these highly stretchable textiles, but also because the applied method was force control. Due to their tendency to not unravel, 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 3. Two samples were tested for Ogliastra, A and B, and one for Levanzo, identified as C, because of the limited amount of textile. The three cuts that go along the arms of the cross aim at distributing tensile stress evenly throughout the central testable square. A portion of 1/3 of each side was assigned to clamping purposes.

A customized clamp was developed in order to uniformly stress the sample. For this purpose, an aluminum profile that is commonly used in textile architecture installation was cut to the right dimensions for each of the four sides and attached to the motors of the machine. The fabric was then wrapped around a keder and slid in the profile with the help of a thin, coated textile patch that prevented knitted loops from getting damaged in the process. In addition, all the samples were folded and sewn near the clamping line to form pockets that would host the keders, hence providing better control over the alignment of the textile and preventing its slippage. The clamping system and sewn seams are shown in Figure 4. LVDT transducers were used as strain-measuring tools, one in warp and one in fill direction.

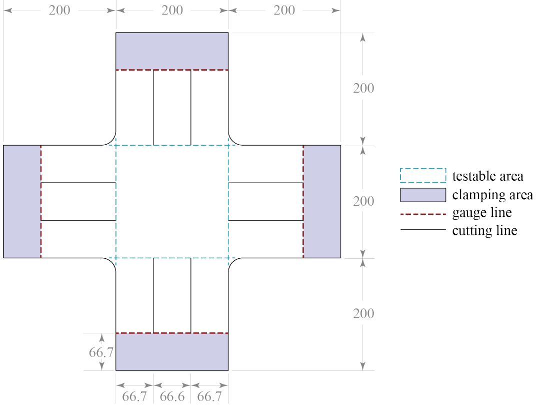

Figure 3. Illustration of sample dimensions in mm and cutting for biaxial testing

However, the most challenging part of biaxial testing was defining the load history to apply to the textile. According to the EN 17117:2018 standard, the peaks of the forces applied should be equal to 1/4 of the UTS and the load profile should include cycles with load ratios of 1:1, 2:1 and 1:2. Based on the uniaxial tests of the fabrics, 1/4 of the UTS resulted to be too high because in this portion of the stress/strain graph Ogliastra and Levanzo already reach a considerable irreversible deformation. Thus, loads from the initial part of their stress/strain graphs were taken and building the load profile was based on design and feasibility considerations. A comparison of the customized three profiles is shown in Figure 5. All the samples were tested according to the loading profile after an initial pretensioning of 5 N per side to achieve a planar specimen, similarly to uniaxial tests. The loading rate during tests did not exceed 4mm/min.

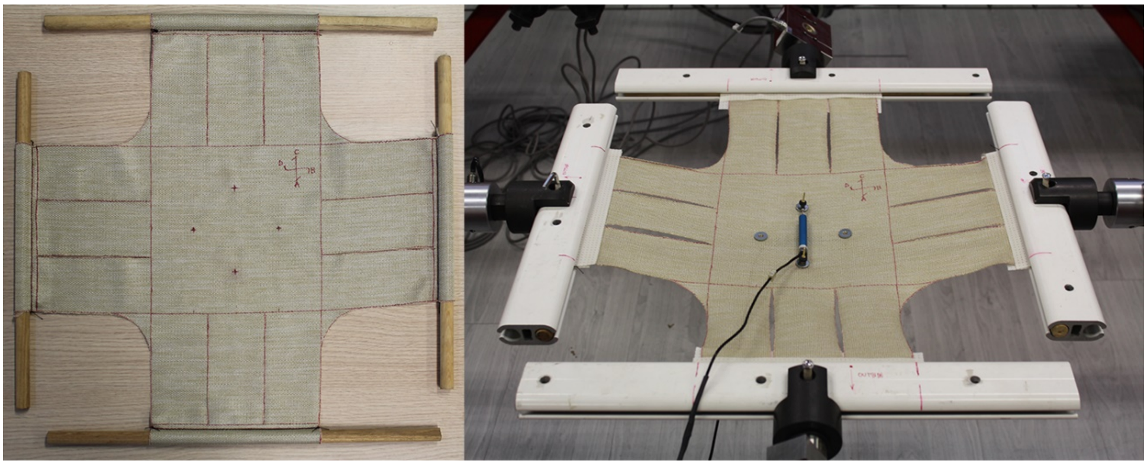

Figure 4. On the left: sample with the keders inserted in the pockets. On the right: the sample placed into the profiles and then attached to the motors.

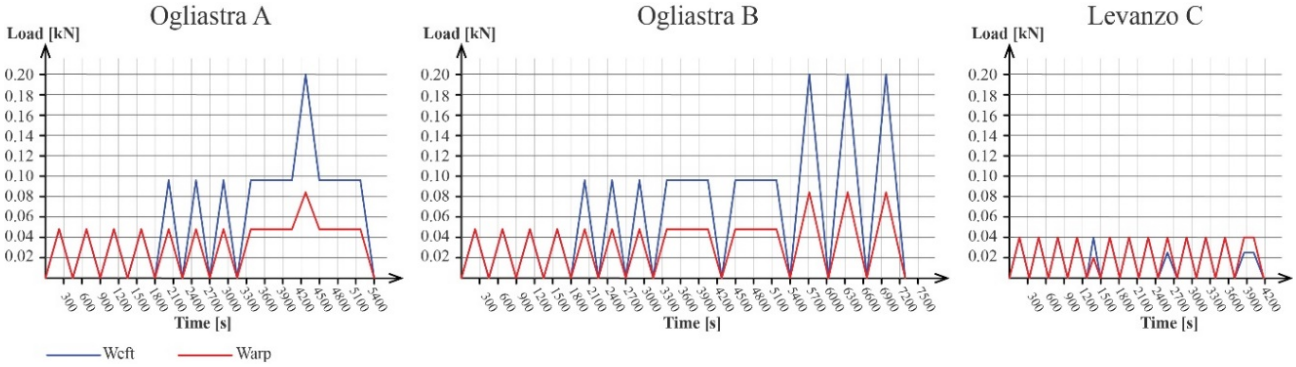

Figure 5. On the left: sample with the keders inserted in the pockets. On the right: the sample placed into the profiles and then attached to the motors.

In the case of Ogliastra, as the design foresees installing the textile vertically, it will be pulled more in weft direction. Also, it will have to stay tensioned for a long period of time, during which it could potentially be subjected to sudden additional loads from an object or person falling into the structure. Thus, the load profile consists of four initial conditioning cycles meant to straighten the material with an equal load in both directions, three cycles of a higher load on weft direction and a plateau that is interrupted in the middle by a peak simulating the sudden accidental impact. Loads in the parts where weft stress is higher were calculated as corresponding to the strain of 15% in both weft and warp. A second load profile was applied to sample B of Ogliastra, this time not taking into consideration a sudden accidental load, but just applying a plateau and three subsequent separate peaks to test the material's elasticity. The load profile of Levanzo on the other hand was customized in a different way. Since this textile is produced to a maximum width of 175 cm, which is the minimum offered by the producers, it was concluded that Levanzo would most likely be used in an horizontal way, connected by few sewn seams, instead of vertically. Thus, because of the uncertainty of the textile's future application, the MSAJ M-02-1995 model was used as a reference for this load profile. However, 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 load profile consists of four initial cycles for straightening the material similarly to Ogliastra, 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, but this time in warp instead of weft since Levanzo will be likely tensioned in that direction.

Table 1. Types of samples and codification

Ogliastra A1	Ogliastra A2	Ogliastra B	Ogliastra B1	Levanzo C
Sample A first test	Sample A retested	Sample B first test	Sample B washed and retested	Sample C first test

A final 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, has been evaluated. For this purpose, the Ogliastra A and B were retested with the same corresponding load profiles and sample Ogliastra B was also washed (water temperature 30°C) to assess the shrinkage of the textile (Table 1). 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.

3 Results and discussions

3.1 Uniaxial test results

Uniaxial tensile tests revealed that Ogliastra withstands higher loads than Levanzo in terms of UTS. However, this implies that Levanzo requires a smaller force to be stretched to the same extent as Ogliastra, which makes it easier to handle on site and assembly. Nevertheless, the interest of the study is focused on elastic deformation and thus stress/strain graphs provide more insight than data at rupture. For this purpose, in Figure 6 three specimen testing results for each of the four specific cases are superimposed in four graphs and then an average curve is traced to represent Ogliastra in weft and warp as well as Levanzo in weft and warp, similarly to Table 1.

It is notable how the curve is changing in the first part of stress-strain diagrams; a change of the slope is visible. The reasons are not completely clear but two possible answers are reasonable: 1. the knitted configuration of the fabrics, which need huger elongation and orientation and tensioning of the fibers (the configuration is soft and the fibers folded due to the stitches) to start to be loaded; 2. a similar but reversed (in the ratio strain - stress) slope accurses testing reinforcing steel, which nevertheless demonstrates activation of fixing wedges of the testing machine, not properties of the tested material. Creep tests on the material itself weren't conducted: this could help to clarify this initial slope's inclination.

The graphs show the strain percentage and the respective stress per sample width, which as stated previously, is equal to 50 mm. The mechanical behavior can be analyzed well if the averages are to be extracted and compared side by side per material and per direction, as in Figure 7. The graphs show that Ogliastra extends more in warp for the same force. However, Levanzo starts from a limited production width that is smaller than Ogliastra's, namely 1.75 m as opposed to 1.85 m respectively, and thus the degree of compliance to the design requisites is the same for both textiles.

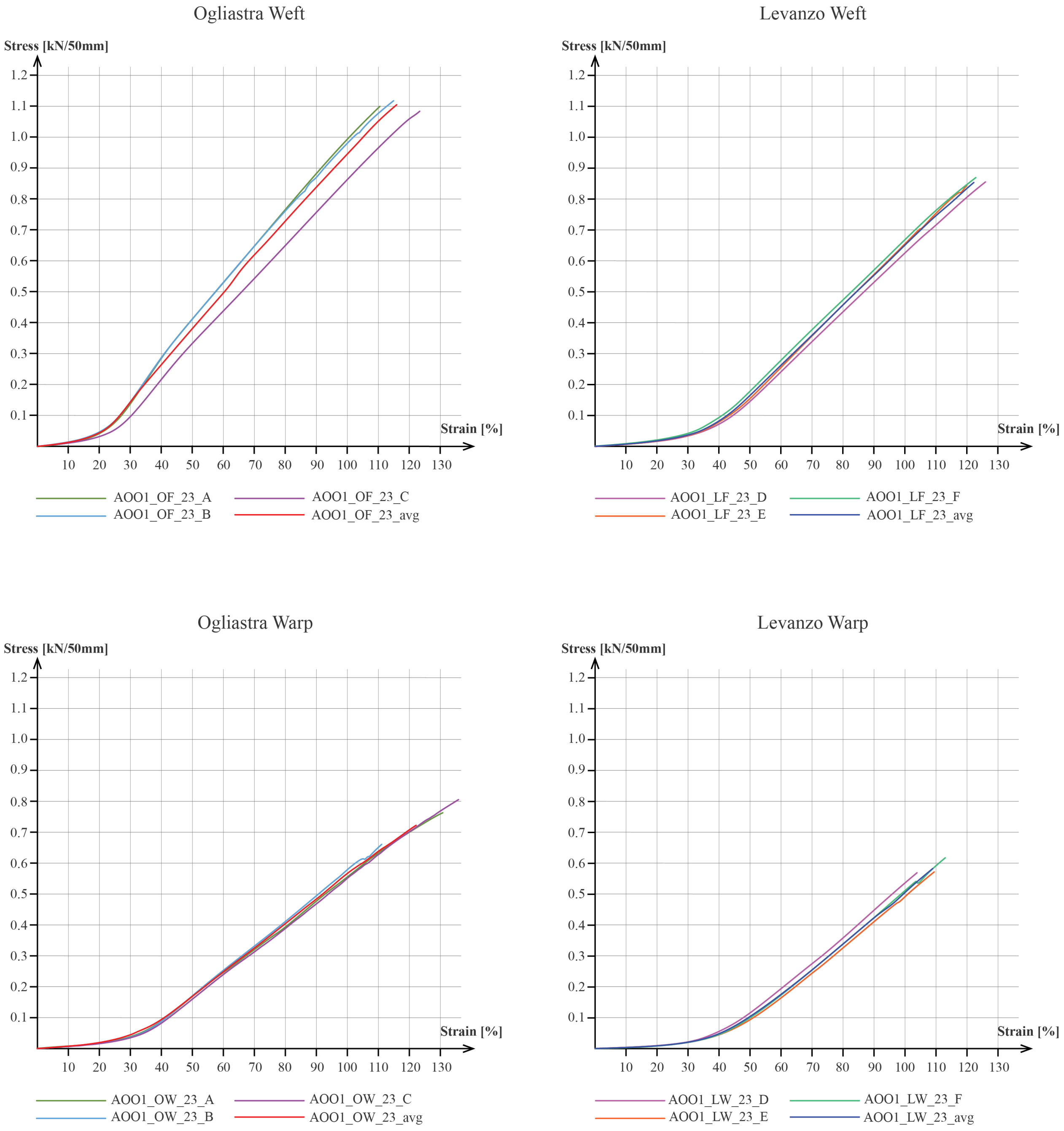

Figure 6. Stress/strain graphs showing the data acquired from the twelve uniaxial tests.

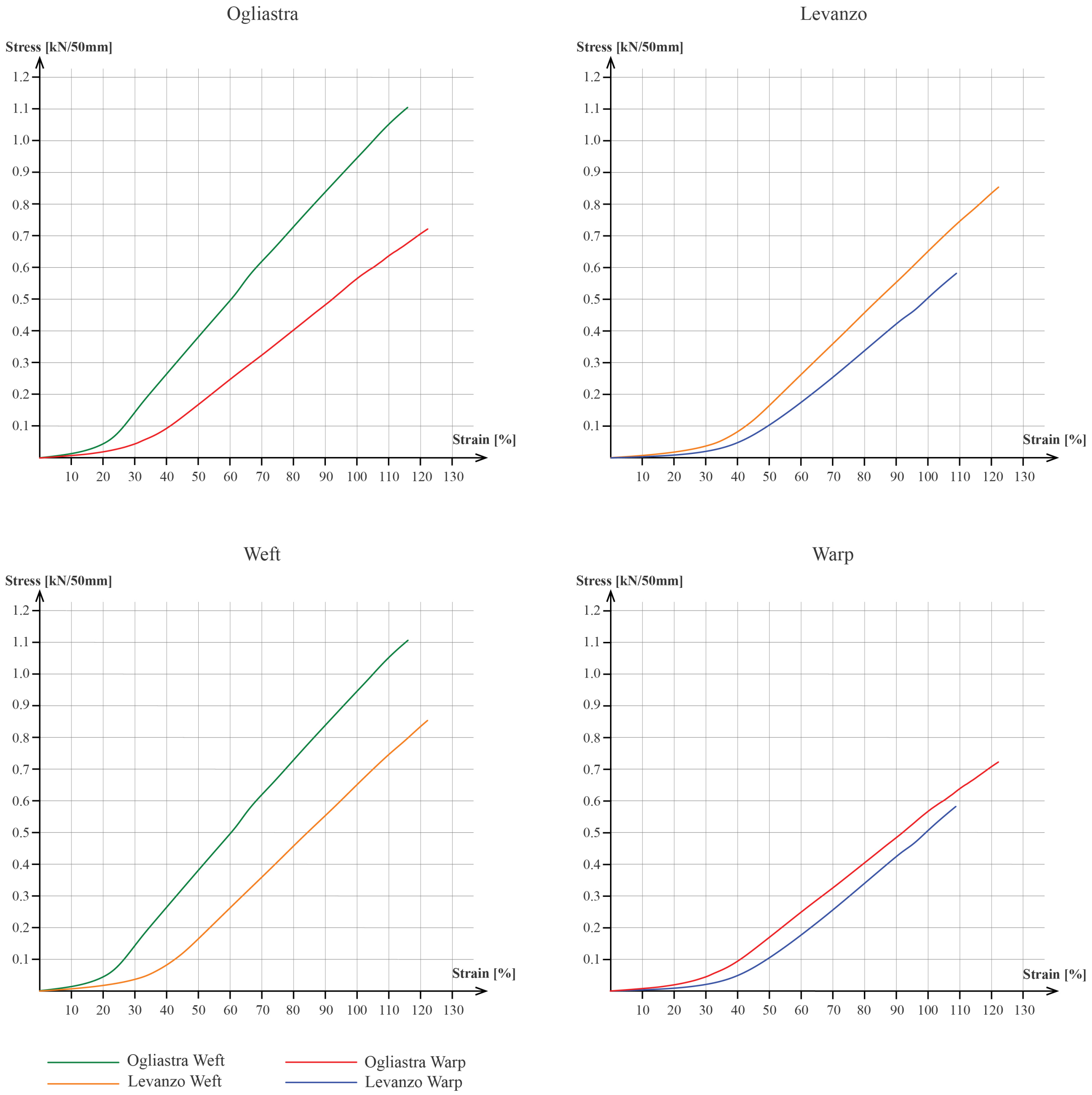

Figure 7. Side by side comparison of stress/strain graphs of the knitted textiles

In addition, all these observations are focused on the failure point since the nature of uniaxial tests is to show the extreme of the loads a material can withstand. However, in this specific case the textile will not be subjected to high loads and the goal shifts to defining the ability to stretch the fabric to the desired extent without making it lose its elasticity. Even though knitted textiles have pure elastic elongation in the first 1-2 % of strain because their substructure remains in place after stretching [19], we were interested in minimizing plastic elongation. All graphs exhibit a clear break in their curves where the slope takes an upward turn and then becomes constant again. To show this sudden change and where it happens, the slope is represented in Figure 8 with a graph for each material and it is superimposed to the corresponding stress/strain graph. The grey areas of the graphs show where plastic deformation is prominent. The thresholds of 10 % for Ogliastra weft, 17 % for Ogliastra warp, 19 % for Levanzo weft and 25 % for Levanzo warp are much lower than the design requisite of 50 % elongation.

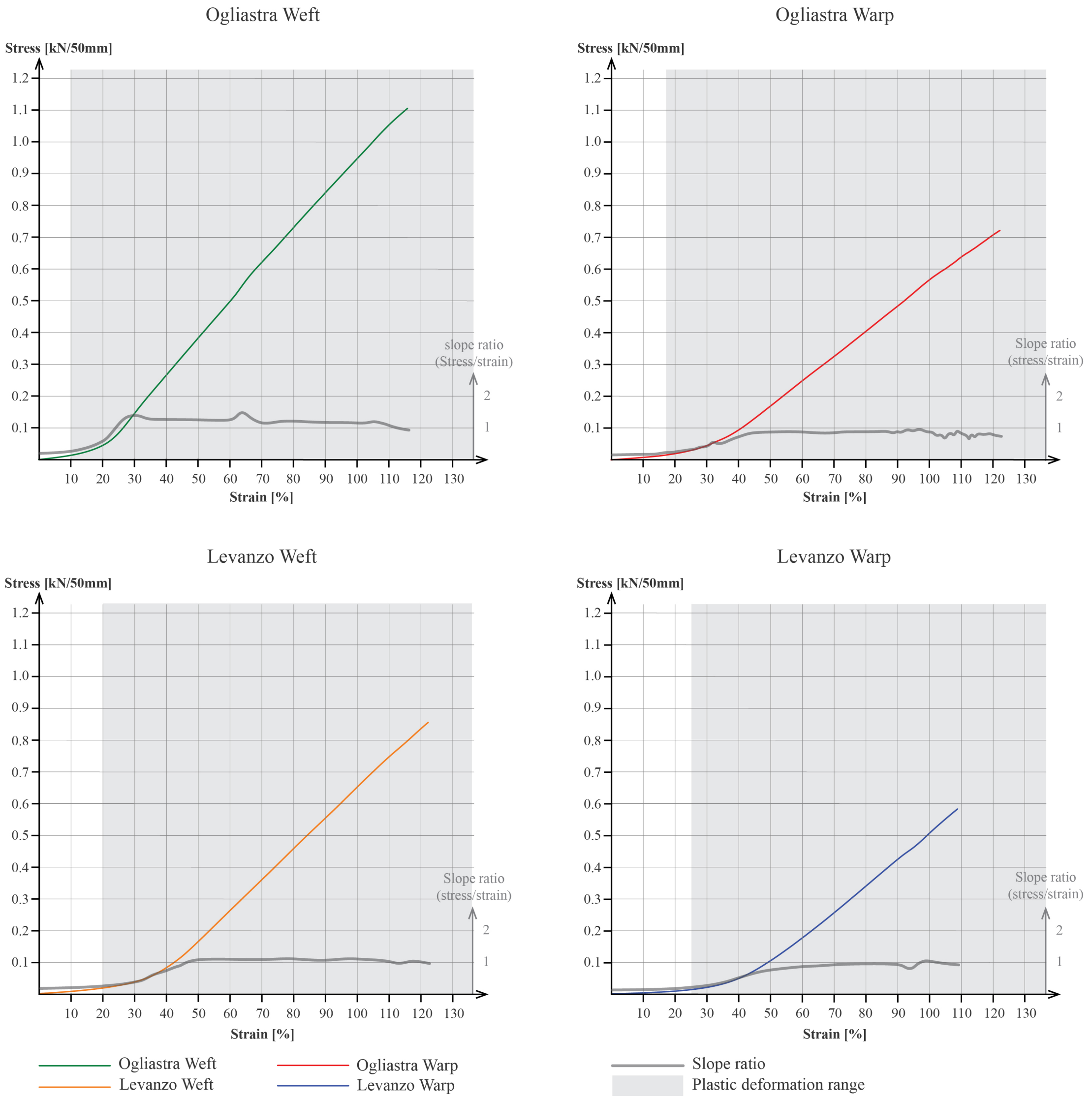

Figure 8. Slope ratio graphs corresponding to stress/strain graphs

3.1.1 Feasibility considerations

As far as feasibility is concerned, stretching needs to have an acceptable force threshold in order to be tackled by workers on site, since the massive area of the textile does not allow a machine to be used for that purpose. A width of at least 1 meter should be taken into consideration since the tests are applied to a very narrow sample of 50 mm, thus the stress should be multiplied by 20. An assumption would be that four workers would stretch the fabric in its four corners and since each of them has an average maximum pulling capacity of 0.4 kN as per [22], the overall limit of the force would be 1.6 kN and thus 0.8 kN per side. That translates in the graph to a 0.04 kN/50mm. This is already a low threshold without taking into account the elastic versus plastic areas of the graph. In the case of Ogliastra it means it is impossible to stretch it more than 19.2% weft-wise and 28.7% warp-wise. For Levanzo the maximum allowed elongation in weft direction is 31.1% while in warp it is 37.7%. However, these considerations are based on the assumption that only pure manpower will be used to stretch the fabrics, thus they serve as mere guidelines. There are different options that could involve levers or rolling gear mechanisms that could amplify the force that is transferred to the fabric. Thus, the main setback for the feasibility of the project remains the high degree of irreversible plasticity of the knitted fabrics, which means that sewn seams are necessary.

3.2 Biaxial test results

Biaxial tests were informed by the results of uniaxial tensile tests, which provided the right loading to input in the load history for each sample. Their aim was also to test whether the assumptions made on the plastic elongation of the textiles were correct. What is obvious from the graphs that show elongation and load over time (Figure 9) is that the textiles stretched far less than the expected 15% for Ogliastra and 21% for Levanzo. This confirms that the biaxial testing method is closer to the real behavior of the fabrics, because when stretched in both directions, the loads act in a combined way, thus blocking elongation in one of the directions. However, even if the samples' extension was smaller than expected, they did not return to their original size. Ultimate plastic deformation ranges from 0.1 to 8 % depending on the load profile that was used, as seen in Figure 9. The maximum of 8 % is reached in the case of Ogliastra B because of the high loads applied in the last three peaks, thus they were removed from the load history in retesting (B1). The lowest plastic deformation is understandably exhibited by Levanzo, not only because of the small-applied loads and absence of forced peaks, but also because of the balance between weft and warp in loading as a consequence of the alternating 2:1 cycles. Thus, it can be inferred that the knitted textiles deform irreversibly in the case of sudden unexpected loads, but they hold their shape best when they remain tensioned in a balanced way in both directions.

In terms of material inconsistencies, the graphs in Figure 10 show that the two different samples of Ogliastra, which came from two different production rolls, exhibit a similar behavior. Thus, the influence of different samples or production rolls is not significant. The only thing that differs is the plateau-peak when compared to the peak, but this shows that the load causes more ultimate plastic deformation when the load is continuously growing. Thus, this behavior is a consequence of the different load profile and not a production inconsistency. This conclusion proves that the lack of multiple samples to test for Levanzo is not a drawback in assessing its mechanical behavior. In fact, Levanzo has the most optimized load profile due to the previous considerations made on Ogliastra samples and, as seen from the results in Figure 9, almost entirely returns to its original state. This happens because of the mirroring balancing effect of the 1:2 cycle that follows the 2:1 cycle.

Retesting the samples, even though unprecedented in existing research, was a practice that provided useful insight into the remounting scenario. When comparing Ogliastra A1 to A2 (A2 is the same sample retested), it can be observed that the results have almost the same behaviour, but translated along the strain axis (Figure 11). This means that because of the peak in weft direction when tested the first time, Ogliastra

A did not return to its original size. Thus, during the first four preconditioning cycles, the knit substructure of the sample was straightened and weft yarns went in compression with respect to the new bigger size in order to reach the original size. This seems to be fixed in the case of B1, which was the test after washing sample B. In conclusion, washing the textile acts as a form of preconditioning because it retracts and straightens the weft fibers, which are expected to shrink by 2-4% when washed, as defined by the producer [9]. This technique could be also applied after an accidental load has been imposed on the structure and has caused a certain plastic deformation.

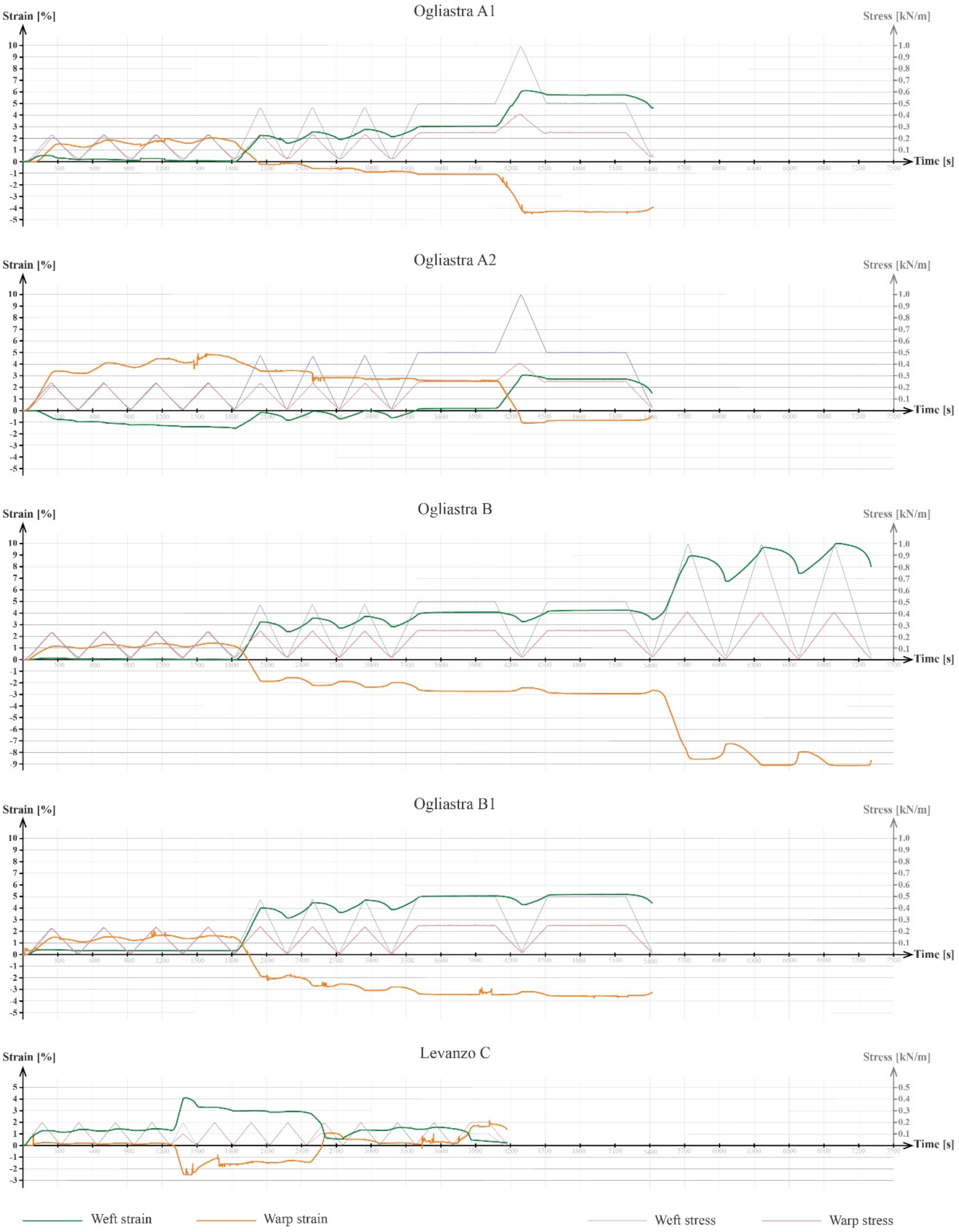

Figure 9. Graphs showing changes in weft and warp strain over time, superimposed over the corresponding load profiles

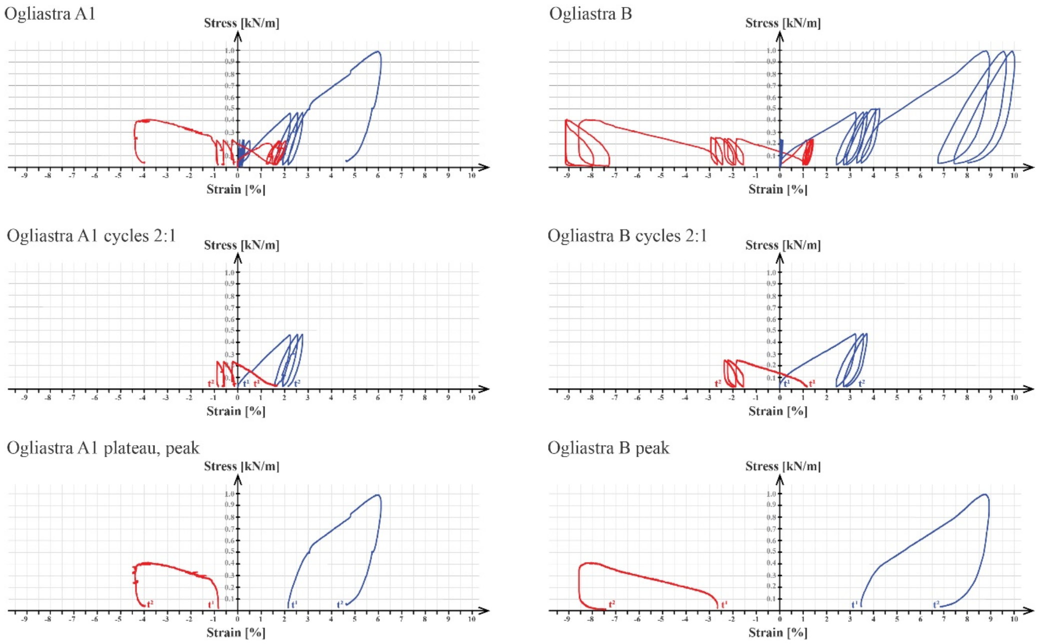

Figure 10. Side by side comparison of biaxial stress/strain graphs of Ogliastra A1 and B. Top: complete graph comparison. Middle: 3 cycles with a loading ratio of 2:1 weft-warp. Bottom: graph of plateau and peak for A1 compared to the first peak applied to B.
The progression over time is marked on the graphs as starting from t^1 and finishing at t^2.

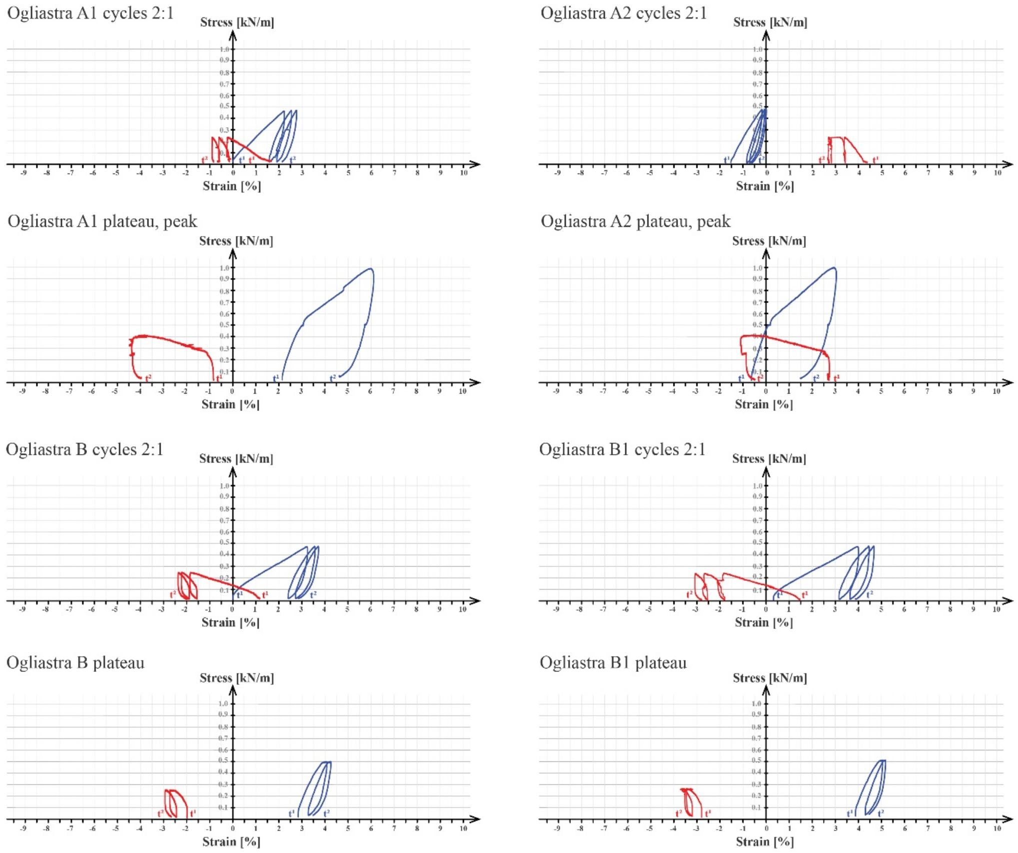

Figure 11. Side by side comparison of retested samples.
The progression over time is marked on the graphs as starting from t^1 and finishing at t^2.

4 Conclusions

This study investigates the mechanical behavior of knitted textiles by means of uniaxial and biaxial tensile testing in order to inform the architectural design process. In this regard, uniaxial tests contributed to initial considerations on the feasibility of a seamless tensile project. A comparison was made between the two fabrics and Levanzo proved to be easier to be handled on site, in addition to extending to a higher elastic elongation. Test results showed that it would be difficult to fulfill the design requirements of reassembly and stability without employing sewn seams, or without updating the manufacturing process, allowing for novel structural applications of knitted textiles. In addition, the elongation assessed in a uniaxial manner overestimates the real elongation because of isolating the directions of weft and warp and considering them as independent from each-other. This was confirmed by the biaxial tests that followed, even though it should be noted that uniaxial testing was crucial to the calibration of biaxial sample loading. As far as the customized load profiles are concerned, they provided important insight into the real behavior of the textiles throughout their installation and lifecycle. Not using the MSAJ standard in the load history proved to be the right choice because the samples reached plastic deformation in the peaks of the performed tests, that used significantly lower forces than 1/4 of the UTS. Retesting the samples hinted that the material could need straightening after being unmounted and reinstalled, depending on how high were the loads it endured while being in tension. Testing the washed sample proved that shrinkage due to washing helps in straightening the fabric after unmounting. This confirmed that, if maintenance includes washing, the reinstalled textile has a similar behavior to the original textile in the beginning of its lifecycle, which is very beneficial to the project. However, this remains experimental and further research could be conducted on the optimization of these load profiles and on applying them to other projects in the field of construction.

5 Acknowledgments

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